The New Banyan-Based Switching Fabric Architecture Composed of Asymmetrical Optical Switching Elements

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Abstract—In this paper, we propose the new architecture of the optical switching fabric which is based on the baseline switching network. Traditional baseline switching networks are composed of \(2 \times 2\) (or \(d \times d\)) switches. The new architecture considered in this paper is constructed from \(2 \times 2\), \(3 \times 3\), \(2 \times 3\) and \(3 \times 2\) switching elements. We show that the proposed architecture requires less crosspoints than the traditional baseline architecture. We assumed an optical application, where semiconductor optical amplifiers are used as the optical switching elements. The proposed structure requires fewer number of active elements as well as passive optical splitters and combiners than the traditional baseline switching fabric. It also contains one stage fewer than the banyan network (therefore we called it the \(\log_2 N - 1\) switching fabric), which results in lower signal losses, distortions, and crosstalk.

1. INTRODUCTION

One of the well known structures of switching networks is the three-stage Clos network described in [1], [2]. Another architecture often considered in the literature is the baseline switching network [3]. This kind of network is also called the \(\log_2 N\) switching network and was often used as an interconnection network in multiprocessor systems [4]. This structure was extended by Shyy and Lea in [5], to the multi-\(\log_2 N\) switching network by connecting several \(\log_2 N\) networks in parallel. Such structures are also called \(\log_2(N,0,p)\) switching networks and each copy of \(\log_2 N\) network is called a plane. By adding \(m\) extra stages to each copy of the \(\log_2(N,0,p)\), so called \(\log_2(N,m,p)\) switching networks have been proposed. These switching networks are composed of \(2 \times 2\) switches. The general case of this kind of network is the \(\log_d(N,m,p)\) switching network composed of \(d \times d\) switches, discussed in [6], [7]. The special case of \(\log_2(N,m,p)\) switching networks is the Cantor network described in [8], [9] and [10] or the \(\log_2 N\) switching network build from \(3 \times 3\) switching elements [11]. More architectures and their properties are described in [12], [13] and [14].

The \(\log_2(N,m,p)\) switching networks are specially attractive for optical switching, since optical technologies mostly enable to construct \(2 \times 2\) switching elements [15]. Recently, it was shown in [11], that in the case of optical switching fabrics composed of semiconductor optical amplifies (SOAs), switching fabrics composed of \(3 \times 3\) switches are more effective than the one composed of \(2 \times 2\) ones. This is especially important since the cost of SOAs is much higher than the cost of splitters or combiners.

The \(\log_d N\) switching network is build from \(d \times d\) switching elements (SEs). The \(\log_d N\) switching fabric has \(N\) inputs, \(N\) outputs, and the number of stages is equal to \(n = \log_d N\). That is why this kind of architecture is called \(\log_d N\). Moreover, each stage consists of \(\frac{d^2}{2}\) switching elements \(d \times d\).

The \(\log_2 N\) switching network is a particular case of \(\log_d N\) switching network which is build from \(2 \times 2\) SEs. In general the number of inputs and outputs in SEs are equal to each other. In some implementations of optical switching elements (OSE), combiners, splitters (they combine and split an optical signal, respectively) and semiconductor optical amplifiers (SOAs) are used. The simple example of the OSE of size \(2 \times 2\) is shown in Fig. 1(a). This OSE has two splitters at the input side, two combiners at the output side, and four SOAs.

In this paper we propose to construct the baseline type switching fabric from OSEs of different capacities: \(2 \times 2\), \(3 \times 3\), \(2 \times 3\) and \(3 \times 2\). As the result we obtain also the switching fabric of capacity \(N\) (\(N\) being the power of 2) but composed of fewer optical elements than their counterparts composed of \(2 \times 2\) or \(3 \times 3\) OSEs.

The new proposed architecture contains also one stage less than the baseline switching network of the same capacity. Optical signal is attenuated by splitters, combiners, and amplified by SOAs in the switching fabric. This influences the quality of an optical signal, especially signal-to-noise ratio (SNR) and crosstalk. The number of SOAs an optical signal can goes through before regeneration (usually more expensive than amplification) is limited. Therefore, fewer number of stages has direct influence on the signal quality and the cost of the whole optical switch.

The paper is organized as follows. In section II, the new architecture is described. Next, the routing in the baseline and in \(\log_2 N - 1\) switching networks are described and some examples of routing in the new structure are shown. In Section IV, the cost analysis is done for the new architecture and compared with the baseline switching networks. Next, crosstalk and signal-to-noise ratio are described, followed by conclusions.

II. THE NEW SWITCHING FABRIC ARCHITECTURE

The new switching network architecture proposed in this paper is based on the traditional baseline \(\log_2 N\) switching fabric. Example of the \(\log_2 8\) switching network is shown in

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Fig. 2(a). The proposed structure in this paper consists of optical switching elements of different sizes, namely: $2 \times 2$, $3 \times 3$, $2 \times 3$ and $3 \times 2$. Structures of $2 \times 2$ and $3 \times 3$ optical switching elements composed of SOAs are shown in Fig. 1(a) and (b), respectively. OSEs of size $2 \times 3$ and $3 \times 2$ are also shown in Fig. 1(c) and (d), respectively. The new architecture has $N$ inputs, $N$ outputs, where $N = 2^n$, and is built from $n - 1$ stages, where $n = \log_2 N$. Thus, we called this architecture the $\log_2 N - 1$ switching network. The minimal size of the $\log_2 N - 1$ switching fabric is $8 \times 8$. The base for this $\log_2 8 - 1$ switching network is the $\log_2 9$ network. The $\log_2 8 - 1$ switching fabric is received by deleting one input of the middle switch in the input stage and one output of the middle switch in the output stage. This new structure is composed of four $3 \times 3$ OSEs, one $2 \times 3$ OSE, one $3 \times 2$ OSE and it is shown in Fig. 2(b). The $\log_2 8 - 1$ switching network constitutes the base to build the switching network of capacity $N = 16$. The $\log_2 16 - 1$ switching fabric is used to construct the $\log_2 32 - 1$ switching network, etc. In general, the $\log_2 N - 1$ switching network is based on the $\log_2 \frac{N}{2} - 1$ switching fabric.

The $\log_2 N - 1$ switching fabric is obtained from the $\log_2 \frac{N}{2} - 1$ switching fabric in the following way:

1) Remove all $2 \times d$ OSEs from the first stage of $\log_2 \frac{N}{2} - 1$ switching network ($d = 3$ for $N = 16$ and $d = 2$ for $N > 16$), all interstage links between these OSEs and OSEs in the second stage, and all unnecessary inputs of OSEs in the second stage (applies only to OSEs in the second stage which were connected to deleted OSEs of the first stage).

2) Made a copy of the switching network obtained in step 1 and put it below the first network. These two networks together now have $N$ outputs.

3) Add the input stage, which is the mirror image of the output stage OSEs. This stage is now the first stage of the $\log_2 \frac{N}{2} - 1$ switching fabric and the first stages of both $\log_2 \frac{N}{2} - 1$ switching fabrics, which now constitutes the second stage of the new switching fabric.

4) Connect outputs of the first stage OSEs with inputs of the second stage switches using the perfect unshuffle pattern [12].

Pursuant to the algorithm presented above, we can build a switching network of capacity $N = 2^n$, where $n \geq 4$. The $\log_2 16 - 1$ switching network is shown in Fig. 3. This switching fabric is obtained in the following way. Firstly, the $2 \times 3$ OSE is removed from the input stage in the $\log_2 8 - 1$ switching network (denoted as $I_2$ in Fig. 2(b)). The proper interstage links are deleted and also some inputs in OSEs from the second stage are removed. Now, the obtained switching network has six inputs and eight outputs. This switching network is duplicated in the second step. The resulted switching fabric has twelve inputs and sixteen outputs. In this step the additional stage at the input side of the structure is also added. This additional stage is the mirror image of the output stage and it is built from six OSEs: two $2 \times 2$ switches and four $3 \times 2$ switches. The additional stage is connected to the rest parts of the switching network of size $12 \times 16$ in accordance with the perfect unshuffle interconnection pattern. Finally, the received structure is the $\log_2 16 - 1$ switching fabric. It can be used as the base to construct the $\log_2 32 - 1$ switching network (see Fig. 4).
### III. Routing

#### A. Routing in the Baseline Switching Network

In the baseline switching network of capacity $N$, outputs are generally numbered in the decimal representation from 0 to $N-1$. They can also be numbered in the binary representation. For example, the third output in the decimal representation is denoted as 2 and in the binary representation is denoted as $[10]_b$. Using the binary representation the number of output can be used to route a connection through the switching fabric. Let us consider a simple example of the log$_2$8 switching network from Fig. 2(a). The fourth output has code $[011]_b$, and the eight output has code $[111]_b$. Each bit directs connection in the relevant stage. This switching network has capacity $N = 8$ so the number of stages is equal to $n = 3$. Suppose that connection $(0, 5)$ is already set-up (see Fig. 2(a)). In this case the code of the output is $[101]_b$. The first bit routes the considered connection through the switching element in the first stage, the second bit routes the considered connection through SE in the second stage and the third bit routes this connection through the SE in the last stage. If the value of the bit is equal to 0, then the considered connection goes through output number 0 in a SE, when the value of the bit is equal to 1, then the connection goes through output 1 in a switching element. In our example, connection $(0, 5)$ goes through the second, first and second output in the SEs in the successive stages, respectively. It should be notice, that the same code allows us to route another connection from any input to this output. For example, connections $(6, 5)$ and $(4, 5)$ shown in Fig. 2(a) are routed to the same sixth output using the same code $[101]_b$. This feature means that the baseline switching network is selfrouting.

#### B. Routing in the log$_2$N − 1 Switching Network

The log$_2$N − 1 switching network has $N$ inputs, $N$ outputs and $n = \log_2 N − 1$ stages. This structure is built from optical switching elements of capacities: $2 \times 2$, $3 \times 3$, $2 \times 3$, and $3 \times 2$. The stages are numbered from $s_1$ to $s_n$, where $s_1$ denotes the input stage and $s_n$ denotes the output stage. The last stage has always $\frac{N}{2}$ OSEs of size $d \times 3$ and $\frac{N}{2}$ OSEs of size $d \times 2$, where $d = 3$ for switching networks of capacity $N = 8$ and $d = 2$ for switching networks of capacity $N \geq 16$. The stage $s_{n-1}$ consists of OSE of size $d \times 3$, where $d = 2$ for the switching networks of capacity $N \geq 32$ and $d = 3$ for the switching fabrics of capacity $N = 16$ (see Fig. 3). In the log$_2$8 − 1 switching network this stage $(s_{n-1})$ contains optical switching elements of size $2 \times 3$ and $3 \times 3$ (see Fig. 2(b)).

The log$_2$N − 1 switching fabric can also be selfrouting, but in this structure each bit from binary representation of an output should be understand in another way, not like it was in the baseline switching networks. We need log$_2$N bits to route any connection through the switching fabric. log$_2$N bits in the baseline switching network are needed, too. However, in the log$_2$N − 1 switching fabric, the number of stage $s_x$, where $x = 1, 2, \ldots, n-1$, $n$ is very important.

The minimal log$_2$N − 1 switching fabric capacity is $N = 8$, so there are always 3 or more bits in the binary representation of each output number. Denote these bits as $a$, $b$ and $c$. For example, output 6 has the binary code $[110]_b$, so $a = 1$, $b = 1$ and $c = 0$. If the capacity of the optical switching network grows, there are more than three bits in the binary code which denotes the output number. For example, when $N = 64$ then output 6 will be denoted as $[b(1) b(2) b(3) abc]_b$, where $b(1) = 0$, $b(2) = 0$, $b(3) = 0$, $a = 1$, $b = 1$ and $c = 0$ or just simple $[000110]_b$. Bit $b(z)$ is responsible for routing a connection in stage $s_z$, where $1 \leq z \leq n - 2$.

The log$_2$8 − 1 switching network with binary representation of each output number is shown in Fig. 5. For outputs 3 and 4 two last bits are always equal to each other $(b = c)$, for outputs 0, 1, and 2 the first bit is always equal to 0 $(a = 0)$ and for outputs 5, 6, and 7 the first bit is always equal to 1 $(a = 1)$. This dependence is very helpful and it can be extended to the general case. It allows us to choose the proper output in SEs in stages $s_n$ and $s_{n-1}$. In stages $s_{n-y}$, where $2 \leq y < n$, each OSE has only two outputs, therefore one bit is enough to route a connection through this switching element.

We can distinguish three routing cases in log$_2$N − 1 switching network, the first for stage $s_n$, the second for stage $s_{n-1}$ and the third case for other stages $s_{n-y}$, $2 \leq y < n$.

**Case 1** — routing in the stage $s_n$. The OSEs in this stage have two or three outputs, so bits $a$, $b$ and $c$ have to be considered. If $a \neq b$ and $b = c$ the considered connection is directed to an OSE with two outputs. In that case, the proper output is chosen according with the bit $a$. If $a = 0$ the considered connection goes through output 0, otherwise $(a = 1)$ the considered connection goes through output 1. If $a = b = c$ or $b \neq c$ it means, that an OSE has three outputs. We choose output 0 when the binary operation $bc = a = [00]_b$ is true, output 1 when $bc = a = [01]_b$ and output 2 if $bc = a = [10]_b$.

**Case 2** — routing in stage $s_{n-1}$. In this case, we consider also three last bits $a$, $b$ and $c$. If $a \neq b = c$ it means that the considered connection goes through output 1 of an OSE in stage $s_{n-1}$. In other case when $a = 0$, the considered connection will be routed through output 0 and when $a = 1$ this connection will be routed through output 2.

**Case 3** — routing in stage $s_{n-y}$, where $2 \leq y < n$. In this case, each OSE has only two outputs, so one bit is enough to choose the proper output. If bit $b(z) = 0$ the considered connection goes through output 0 and when $b(z) = 1$ the considered connection goes through output 1.

#### C. Examples of log$_2$N − 1 switching network selfrouting

We present three examples of selfrouting in the log$_2$N − 1 switching network which correspond to three different routing cases. We explain how bits of binary representation of an output number are used to drive a connection to the proper output of OSEs in each stage.
Example 1. Let us consider the \( \log_2 8 - 1 \) switching fabric. This switching network has \( N = 8 \) inputs, thus it consists only of two stages. In stage \( s_n = s_2 \) (the output stage) there are two OSEs of size \( 3 \times 3 \) and one OSE of size \( 3 \times 2 \). Stage \( s_{n-1} = s_1 \) (the input stage) consists only of the optical switching elements with three outputs. Suppose that connection \( \langle 1, 6 \rangle \) is set up in the switching network (see Fig. 6(a)). Output 6 has code \([110]\), therefore \( a = 1, b = 1 \) and \( c = 0 \). At first, connection goes through stage \( s_{n-1} = s_1 \) and it will be routed through output 2 in the first OSE because two last bits are not equal to each other \((b \neq c)\) and bit \( a = 1 \). In stage \( s_n = s_2 \), this connection goes through output 1 in the OSE because \( b \neq c, a = 1 \) and binary operation \( bc - a = [10][b - [1]_b = [01]_b = 1 \).

Example 2. In this example, let us consider the \( \log_2 16 - 1 \) optical switching network. This switching network has \( n = 3 \) stages. In stage \( s_n = s_3 \) there are four OSEs of size \( 2 \times 3 \) and two OSEs of size \( 2 \times 2 \). Stage \( s_{n-1} = s_2 \) consists only of optical switching elements with three outputs. Therefore, in each of these OSEs the way of choosing the proper output will be the same. Stage \( s_{n-2} = s_1 \) consists only of switching elements with two outputs, thus in each OSE the proper output will be chosen similarly as in traditional baseline switching networks. An example for connection routing in OSEs with three outputs was presented in Example 1. Now let us consider connection \( \langle 6, 3 \rangle \) in \( \log_2 16 - 1 \) switching network (see Fig. 6(b)). The first bit from the code corresponding to output 3 is equal to 0, and therefore the considered connection goes through the output 0 in OSE in stage \( s_1 \). Next bits in the binary code are 0, 1, 1 and they are denoted as \( a, b \) and \( c \), respectively. In stage \( s_2 \) the considered connection goes through output 1 because \( b = c = 1 \) and \( a = 0 \) (case 2: \( a \) is different from \( b \) and \( c \)). In stage \( s_3 \) the considered connection goes through output 0 of OSE because \( a \neq b = c \) and \( a = 0 \) (case 1: the proper output is chosen according to the value of bit \( a \)). All other connections directed to output 3 are set up by the same procedure.

Example 3. Let us consider the \( \log_2 32 - 1 \) switching network. This switching fabric has 4 stages and in the last stage there are OSEs with two or three outputs. In stage \( s_{n-1} = s_4 \) all OSEs have three outputs, in stages \( s_{n-2} = s_3 \) and \( s_{n-3} = s_2 \) each OSE has two outputs. Thus, in the optical switching element from stages \( s_3 \) and \( s_4 \) the proper output will be chosen as in the baseline networks (we need only one bit to choose the right output). In stages \( s_3 \) and \( s_4 \), the proper output is chosen pursuant to three last bits \((a, b \) and \( c)\) from the binary code. Let us consider connection \( \langle 19, 19 \rangle \). The binary code for output 19 is \([10111]\) (see Fig. 7). In stage \( s_1 \), output 1 is chosen in OSE since \( b_{s(1)} = 1 \). Considered connection is directed to output 0 of OSE in stage \( s_2 \) because \( b_{s(2)} = 0 \). In stage \( s_3 \) output 1 is chosen, because \( b = c = 1 \) and \( a = 0 \). In OSE in stage \( s_4 \) connection \( \langle 19, 19 \rangle \) goes through output 0, because \( b = c \neq a \) (the proper output is chosen according to the value of \( a \)). All other connections directed to output 19 are set up in the same way as connection \( \langle 19, 19 \rangle \). For example, connections \( \langle 7, 19 \rangle \) and \( \langle 29, 19 \rangle \) are also shown in Fig. 7.

IV. COST FUNCTIONS

The cost of the optical switching fabric is very often expressed as the number of its crosspoints. Each OSE consists of splitters, combiners, and SOAs. Thus, in this paper we also use this cost measure. We assumed that the cost of the optical switching fabric is expressed as the number of its \( s/c \) and SOAs. This idea allows us to compare the cost of different architectures of optical switching fabrics. The architecture which has more of these optical elements is more expensive. Furthermore, to increase the quality of the optical signal, it is very desirable to decrease the number of SOAs which the optical signal goes through in the switching fabric. The cost can be calculated using the cost function \( C(\Omega) = \{\alpha; \beta\} \), where \( \alpha \) denotes the number of semiconductor optical amplifiers (SOA), \( \beta \) denotes the number of splitters and combiners \((s/c)\) and \( \Omega = \{\log_d N; \log_2 N - 1\} \) denotes the architecture of the switching fabric. In the traditional baseline switching network

\[
\alpha = n \cdot \frac{N}{d} \cdot d^2 = nNd,
\]

\[
\beta = n \cdot \frac{N}{d} \cdot 2d(d - 1) = 2nN(d - 1),
\]

where \( n = \log_d N \) denotes the number of stages, \( \frac{N}{d} \) denotes the number of optical switching elements in one stage, \( d^2 \) denotes the number of connections per input.
denotes the number of SOAs in one OSE and \( 2(d - 1) \) denotes the number of s/c in one OSE. For example, the cost of the \( \log_2 8 \) switching fabric shown in Fig. 2(a) is equal to:

\[
C(\log_2 8) = \{3 \cdot 4 \cdot 4; 3 \cdot 4 \cdot 4\} = \{48; 48\}.
\]

This switching network consists of three stages. Each stage has four optical switching elements and each OSE is built from two splitters of size \( 1 \times 2 \), two combiners of size \( 2 \times 1 \) and four SOAs. In the \( \log_2 8-1 \) switching fabric the cost is:

\[
C(\log_2 8-1) = \{2(6 + 2 \cdot 9); 2(5 + 2 \cdot 6)\} = \{48; 34\}.
\]

This optical switching fabric has only two stages and each stage has one OSE of size \( 2 \times 3 \) (or \( 3 \times 2 \)) and two OSEs of size \( 3 \times 3 \). The \( 2 \times 3 \) and \( 3 \times 2 \) OSEs have five s/c and six SOAs. The \( 3 \times 3 \) OSE has six s/c and nine SOAs (Fig. 1(e), (d) and (b), respectively). The cost of the \( \log_2 16 \) switching fabric is:

\[
C(\log_2 16) = \{4 \cdot 8 \cdot 4; 4 \cdot 8 \cdot 4\} = \{128; 128\},
\]

and the cost of the \( \log_2 16 - 1 \) switching network (see Fig. 3) is equal to:

\[
C(\log_2 16 - 1) = \{2(2 \cdot 4 \cdot 4 + 6) + 4 \cdot 9; 2(4 \cdot 5 + 2 \cdot 4) + 4 \cdot 6\} = \{100; 80\}.
\]

The cost of the optical switching fabric of capacity greater than or equal to \( 8 \times 8 \) proposed in this paper is lower than the cost of the traditional baseline switching fabric. If the capacity of the switching network is increasing (\( N = 32, 64 \) etc.) the proposed new structure is also cheaper than baseline switching fabrics (see Fig. 8). Moreover, the difference between the cost of the \( \log_2 N - 1 \) optical switching fabric and the \( \log_d N \) or \( \log_3 N \) [11] networks is increasing (see Table 1). The \( \log_3 N \) switching fabric (precisely described in [11]) is build only from OSEs of size \( 3 \times 3 \). The \( \log_3 N \) and \( \log_4 N \) switching fabrics are build only from s/c of sizes \( 1 \times 2 \) and \( 2 \times 1 \). The \( \log_3 N \) switching network consists only of s/c of sizes \( 1 \times 3 \) and \( 3 \times 1 \). In turn, the \( \log_2 N - 1 \) switching fabric consists of splitters and combiners of sizes: \( 1 \times 2, 1 \times 3, 2 \times 1 \), and \( 3 \times 1 \). It can be seen in Table 1, that the cost of the structure proposed in this paper is lower than the cost of other previously known structures. The cost of the optical switching networks expressed as the number of splitters and combiners s/c (the dotted line) and as the number of SOAs (the solid line) is shown in Fig. 8. It can be easily seen that the cost of the \( \log_2 N - 1 \) is less than the cost of the other previously known baseline structures.

### Table I: The Cost of the Optical Switching Fabrics (N – the number of inputs/outputs)

<table>
<thead>
<tr>
<th>N</th>
<th>( \log_2 N )</th>
<th>( \log_3 N )</th>
<th>( \log_4 N )</th>
<th>( \log_2 N - 1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>(48, 48)</td>
<td>(54, 36)</td>
<td>(48, 72)</td>
<td>(48, 34)</td>
</tr>
<tr>
<td>16</td>
<td>(128, 128)</td>
<td>(162, 108)</td>
<td>(128, 192)</td>
<td>(100, 80)</td>
</tr>
<tr>
<td>32</td>
<td>(320, 320)</td>
<td>(369, 264)</td>
<td>(320, 480)</td>
<td>(224, 192)</td>
</tr>
<tr>
<td>64</td>
<td>(768, 768)</td>
<td>(792, 528)</td>
<td>(768, 1152)</td>
<td>(512, 448)</td>
</tr>
<tr>
<td>128</td>
<td>(1792, 1792)</td>
<td>(1935, 1290)</td>
<td>(1792, 2688)</td>
<td>(1152, 1024)</td>
</tr>
<tr>
<td>256</td>
<td>(4096, 4096)</td>
<td>(4644, 3096)</td>
<td>(4096, 6144)</td>
<td>(2560, 2304)</td>
</tr>
<tr>
<td>512</td>
<td>(9216, 9216)</td>
<td>(9234, 6156)</td>
<td>(9216, 13824)</td>
<td>(5632, 5120)</td>
</tr>
</tbody>
</table>

![Fig. 8. The cost of the switching fabrics expressed as the number of s/c and SOA](image)

**V. Crosstalk**

When the optical signal goes through the OSE it goes through one splitter, one SOA and one combiner (see Fig. 9(a) – the solid bold line). We assume that each input signal has optical power \( P_{in} \). We also assume that one SOA compensates all optical signal losses which are in one OSE. So, the optical power of signal at the OSE’s output (\( P_{out} \)) is, in estimation, equal to the optical power of the input signal, thus \( P_{out} \approx P_{in} \). A crosstalk arises in each OSE as a small part of optical power which influence another signal set up in the same OSE. We assume as in [16] and [17], that a crosstalk is equal to \( P_{noise} = mP_{in} \), where usually \( m = 0.01 \). It means, that it is \( |X| = 20dB \) loss between \( P_{noise} \) and \( P_{in} \) [16], [17]. An example of crosstalk is shown in Fig. 9(a) by dotted line. In Fig. 9(b) and (c), crosstalk in \( 3 \times 3 \) and \( 3 \times 2 \) OSEs is presented, respectively. In this case a crosstalk from two inputs influences a connection (for example crosstalk from input 1 and 2 influences connection \( \langle 0, 0 \rangle \)).

In the baseline optical switching network each OSE has size \( 2 \times 2 \) therefore in the worst case there can be only one crosstalk per stage. Thus, the signal-to-noise ratio is [16]:

\[
SNR(\log_2 N) = |X| - 10 \log_{10}(\log_2 N) \ dB.
\]

In the \( \log_3 N \) optical switching network (described by Small and Bergman [11]) each OSE has size \( 3 \times 3 \) so in the worst case there can be a crosstalk from two inputs per stage. So, the signal-to-noise ratio is equal to:

\[
SNR(\log_3 N) = |X| - 10 \log_{10}(2\log_3 N) \ dB.
\]

For the \( \log_2 N - 1 \) optical switching fabric the SNR is computed analogously, however, we can distinguish two cases. The first case concerns switching networks of capacity 8 and 16, and the second case is related to networks with capacity greater than or equal to 32. In the \( \log_2 8 - 1 \) switching network, crosstalk from two inputs influence a connection in OSE in each stage, because these OSEs has three inputs and three outputs and there can be two additional connections apart to considered connection. In Fig. 9(b) it is
shown the worst state in $3 \times 3$ OSE. In $\log_2 16 - 1$ switching network one crosstalk is present in each OSEs in the first stage, because these OSEs have only two outputs (see Fig. 9(c)). In the last stage there is also present one crosstalk in each OSEs because these OSEs have only two inputs. In the middle stage OSEs, a crosstalk from two inputs influence a middle stage OSEs, a crosstalk from two inputs influence a middle stage OSEs, because these OSEs have only two inputs. In the middle stage 0SEs, a crosstalk which originate from four sources, so signal-to-noise ratio is equal to:

$$SNR(\log_2 N - 1) = |X| - 10 \log_{10}(4) \ [dB].$$

In the case of $N \geq 32$ in each stage there is only one crosstalk, therefore the signal-to-noise ratio is equal to:

$$SNR(\log_2 N - 1) = |X| - 10 \log_{10}(\log_2 N - 1) \ [dB].$$

SNR in different switching network structures is compared in Table II. It can be seen that the new architecture has worse SNR than the baseline network only for $N = 8$. For $N = 16$, SNR is the same and for $N \geq 32$ SNR in the new architecture is always better than in the baseline networks.

VI. CONCLUSIONS

We have proposed the new architecture of optical switching fabrics composed of semiconductor optical amplifiers. This architecture is based on classical baseline topology, but uses optical switching elements of different capacities. As the result, the proposed architecture requires fewer or the same number of SOAs and fewer passive splitters and combiners as other architectures. It has also fewer switching stages, so an optical signal passes through fewer optical elements which influence the signal quality (attenuation, SNR, crosstalk).

Of course it should be noted that the cost of $1 \times 2$ splitter or $2 \times 1$ combiner is not equal to the cost of $1 \times 3$ splitter or $3 \times 1$ combiner, respectively. The total number of $s/c$ in $\log_2 N - 1$ is aggregating splitters of size $1 \times 2$, $1 \times 3$ and combiners of size $2 \times 1$, $3 \times 1$. But even in that case the new structure needs fewer $s/c$ than other structures.

REFERENCES