Paper

Multistage optical switching networks

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Abstract — The backbone networks evolution to high-speed DWDM networks generates new problems for switching. This function element must be also based on optical technology. For large capacity this cannot be realized by a single matrix, but by multistage switching networks. In the paper three types of optical matrices have been described: fiber switch *FX*, wavelength fiber switch *WSX* and wavelength interchanging fiber switch *WIX*. Based on these matrices, four switching network constructions were considered. The connection properties of these switching networks were evaluated, determining the electronic equivalent switching network for which these properties are well known.

Keywords — optical matrix, optical switching networks, electronic switching networks equivalent, connection properties.

1. Introduction

The DWDM technology has increased the transmission capacity of fiber links and transmission systems. Thus the bandwidth bottleneck problem in transmission was overcome. But the backbone transport networks must fulfil two main functions: transmission and switching. The last one is necessary to make connections between users of this backbone network. It is realized by switching nodes of the backbone network. As the capacity of this backbone grows very strongly, the processing power of switching function must keep up with that growth. Thus the connection capability and power processing of nodes must also grow. To reach one's aim some problems must be solved: kinds of switched medium (space, wavelength, time), structure of matrices type, scalability of connection capacity. The solution all of these problems is difficult, as they very strongly depend on each other and great influence on that has the state of technology [1–4].

Now two kinds of medium can be switched: space (fibers) and wavelength. Based on this different type of switching matrices can be constructed. The connection capacity of these matrices is limited by the technology and, for that reason multistage optical switching networks must be used to overcome the capacity problem and realize the switching function. Their connection properties depend on the used matrix types and switching network structure.

In this paper the consideration about matrix types and network structures is presented. For the matrix we account two dimensions: fiber (space) and wavelength. Based on this assumption three types of optical matrix (element, fabric) were introduced: FX, WSX, and WIX. In Section 2 these elements are defined and described from the point of view of connection. The optical switching network can be constructed on these types of matrices and, we can do that in many ways. In Section 3 we have presented four constructions limited only to two side of multistage switching networks. The structures of these constructions are named GS_{FX}, GS_{WSX}, $GS_{WIX\_WSX\_WIX}$ and $GS_{WIX\_WIX\_WIX}$ and are described. To evaluate the connection properties we transform the optical switching network structure into electronic switching network structure. The last one is very well recognized and theoretically described. The results of these considerations are presented in Section 4. Finally Section 5 concludes the paper.

2. Optical switching matrix

We have limited our consideration to three types of optical switching matrix (element, fabric) that will be used to construct the multistage switching networks. The matrices are named: fiber switch FX, wavelength fiber switch WSX and wavelength interchanging fiber switch WIX. Each of these elements is described by the structure parameters, the number a of input fibers and number b of output fibers. The input and output fiber guide n optical waves denoted as $n\lambda$. The general notation of this structure is presented in Fig. 1. We introduce the following sets: fiber input set $A = \{1, 2, \ldots, a\}$, fiber output set $B = \{1, 2, \ldots, b\}$ and wave set $\Lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_n\}$. The connection between an input x and an output y we denote as $c = <x, y>$, where $x = (f^x, \lambda^x)$, $f^x \in A$, $\lambda^x \in \Lambda$ and $y = (f^y, \lambda^y)$, $f^y \in B$, $\lambda^y \in \Lambda$. All of the possible connections form a set $C = \{c : x \in X,\ y \in Y\}$. For each type of element considered in this paper we assume that

$$\underset{c \neq c_1}{\forall} \ \underset{(f,\lambda)}{\forall} \left((f,\lambda) \in c \Rightarrow (f,\lambda) \notin c_1 \right). \tag{1}$$

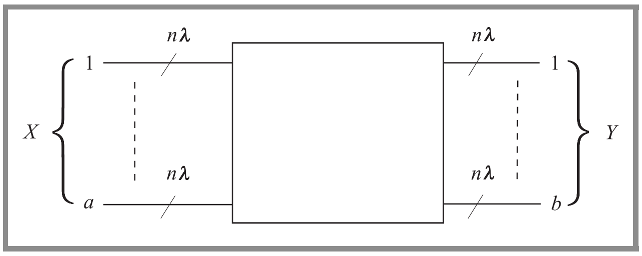

Fig. 1. General structure of optical switching element (matrix).

The FX matrix can connect only the input fibers with the output fibers, but that can be done only one_to_one fiber and has no influence on the n guide waves in these fibers.

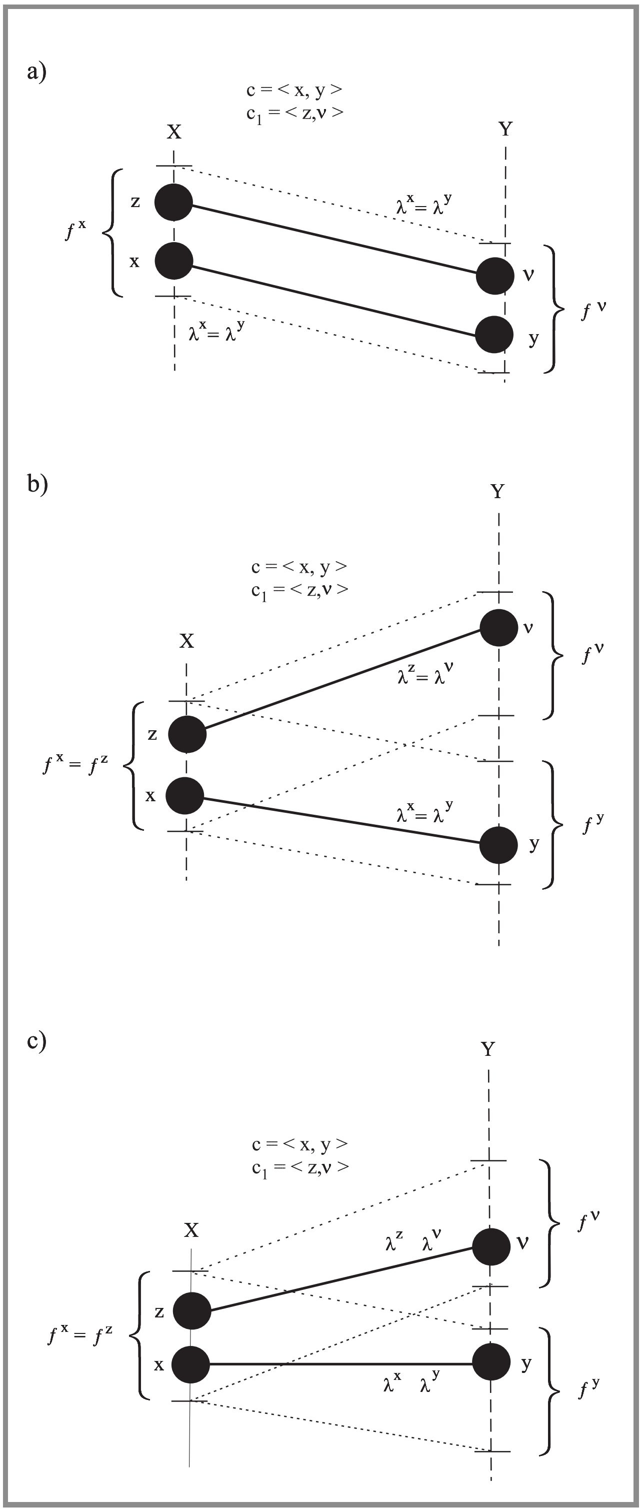

Fig. 2. Connection set C element illustration for matrix type: (a) FX; (b) WSX; (c) WIX.

We say that the connection is wavelength transparent. Let $c=<x,y>$ and $c_1=<z,v>$ then the set C of the connections can be described as

$$C=\left\{c:\underset{x}{\forall}\underset{\lambda}{\forall}\left(\lambda^x=\lambda^y=\lambda\right)\wedge\left(\left(f^x=f^z\right)\Rightarrow\left(f^y=f^v\right)\right)\right\}. \quad (2)$$

Properties of this set are presented graphically in Fig. 2a. For WSX matrix we assume that this element can additionally switch any wave between any input and any output fibers without changing the wavelength. The set C of the connection can be written as

$$C=\left\{c:\underset{x}{\forall}\underset{\lambda}{\forall}\left(\lambda^x=\lambda^y=\lambda\right)\right\} \quad (3)$$

and this is presented graphically in Fig. 2b.
The WIX matrix has additional feature towards the last one. It can change the wavelength of connection between input and output fibers. Connection set C has elements, which fulfil

$$C=\left\{c:\underset{x}{\exists}\underset{\lambda^x}{\exists}\left(\lambda^x\neq\lambda^y\right)\right\}. \quad (4)$$

This feature is presented graphically in Fig. 2c.
All of these matrices are nonblocking. The maximum number $|C|$ of connections is given by formula

$$|C|=n\cdot\min(a,b). \quad (5)$$

In this paper we have not get into consideration the technology of realization the optical switching matrix. It was assumed that the defined matrices, with above described connection properties, are available and based on these matrices the connection capabilities of the multistage optical switching networks were evaluated.

3. Multistage switching networks

Based on switching matrices presented in Section 2 we can construct many types of multistage switching networks. The most interesting are two side switching networks. For these ones we can distinguish four constructions:

- in each stage only FX matrices are used,
- in each stage only WSX matrices are used,
- in the first and last stage only WIX matrices are used and in the remaining stages WSX matrices are used,
- in each stage only WIX matrices are used.

We will later prove that each of these constructions has various connection capabilities, the first one has the worst and the last one has the best.
The switching network structure G is described by four parameters: left W_l and right W_r dimensions of matrices, set W_λ of waves and construction Alg of the connection between matrices belonging to the neighbouring stages.
All of these parameters can be denoted as follows:

- $G=<W_l,W_r,W_\lambda,Alg>$,
- $W_l=<a_1,a_2,\ldots,a_s>$,
- $W_r=<b_1,b_2,\ldots,b_s>$,

– $W_\lambda = < n\lambda_0,\, n\lambda_1,\, \ldots,\, n\lambda_s >$, where $n\lambda_i = \Lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_n\}$,
– *Alg* is an algorithm given by Cantor, Clos, Benes or others [5–7],

where s is the G structure stage number. The switching network capacity can be counted in number N of fiber ports and, in maximum number $|C|$ of connections.
These numbers are given by the following formulas

$$N = \min\left\{\prod_{i=1}^{s} a_i,\ \prod_{i=1}^{s} b_i\right\},\ |C| = n \cdot N. \tag{6}$$

Typical practical switching networks have $GS = GG^{-1}$ structure with $(2s-1)$ stages, where G^{-1} is reversed (mirrored) structure to the G structure. We will now describe this GS structure for four above mentioned switching network constructions.
When all matrices are of FX type then GS_{FX} structure can only connect input fiber with output fiber. The switching network for the wavelength is transparent. The combinatorial power of connection realization depends on W_l, W_r and W_λ parameters. The switching network can be blocking, rearrangeable and nonblocking in strict and wide sense. Theoretical results are given and are just the same as for the analog space switching networks [5–7].

Conclusion 1. The GS_{FX} switching network structure has the same connection properties like the analog space switching network.

In the case when all matrices are of WSX type, the GS_{WSX} structure can be divided into n parallel GS switching networks, each one for different wavelength. Each of these switching networks has similar properties like the GS_{FX} structure and, is described by the same theorems. We must only remember that in the GS structure wave corresponds to fiber in GS_{FX} structure and is an input and output. Each of these structures can be blocking, rearrangeable and nonblocking in strict and wide sense. The connection features of GS structure depend on W_l and W_r parameters. The equivalent switching network of GS_{WSX} structure is presented in Fig. 3.

Conclusion 2. The GS_{WSX} switching network structure has the same connection properties like the n parallel separated analog space switching network.

The third construction $GS_{WIX\_WSX\_WIX}$ based on WIX and WSX type of matrices can be divided into two parts. The first part consists of the first and the last stage and, the second part consists of b_1 GS_{WSX} switching networks with structure parameters as follows: $W_l = < a_2, \ldots, a_s >$, $W_r = < b_2, \ldots, b_s >$, $W_\lambda = < n\lambda_1, \ldots, n\lambda_s >$, where $n\lambda_i = \{\lambda_1, \lambda_2, \ldots, \lambda_n\}$. Each of these GS_{WSX} can be divided into n parallel switching networks like those presented in Fig. 3. Thus the second part of $GS_{WIX\_WSX\_WIX}$ has $n \times b_1$ this one switching network. For this reason when we compare the former described two constructions with the same capacity N and $|C|$ we can say that the combinatorial power of connection realization is greater for $GS_{WIX\_WSX\_WIX}$ than for GS_{FX} and GS_{WSX} structures. $GS_{WIX\_WSX\_WIX}$ structure can be blocking, rearrangeable and nonblocking in strict and wide sense. The connection features depend on W_l, W_r and W_λ parameters.

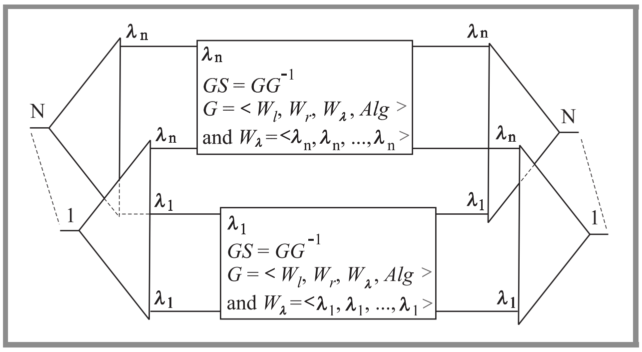

Fig. 3. Equivalent of $GS_{WSX} = GG^{-1}$ structure: $G = < W_l, W_r, W_\lambda, Alg >$ and $W_\lambda = < n\lambda_0, n\lambda_1, \ldots, n\lambda_s >$.

Conclusion 3. The $GS_{WIX\_WSX\_WIX}$ switching network structure has better connection properties than GS_{FX} and GS_{WSX} switching network structures.

The last one, $GS_{WIX\_WIX\_WIX}$ construction is based only on WIX matrices and each matrix can change any input wavelength to any output wavelength. For this reason this construction has the combinatorial power of connection greater than other above-mentioned constructions. This construction can be also blocking, rearrangeable and nonblocking in strict and wide sense. The connection features depend on W_l, W_r and W_λ parameters.

Conclusion 4. The $GS_{WIX\_WIX\_WIX}$ switching network structure has better connection properties than GS_{FX}, GS_{WSX} and $GS_{WIX\_WSX\_WIX}$ switching network structures.

Apart from the two side optical switching networks the one side optical switching networks can be constructed based on the same set matrix types. The most interesting is the structure based only on WIX matrices. This structure has the best connection properties. But all the one side constructions have disadvantages in transmission domain because of different path length in switching network – the number of matrices in connection path is variable. And for that reason these constructions will not be described in the paper.

4. Optical and electronic switching network similarity

Between optical and electronic matrices technology we can indicate similarity with respect of connection capability. The electronic matrices are analog or digital. For analog

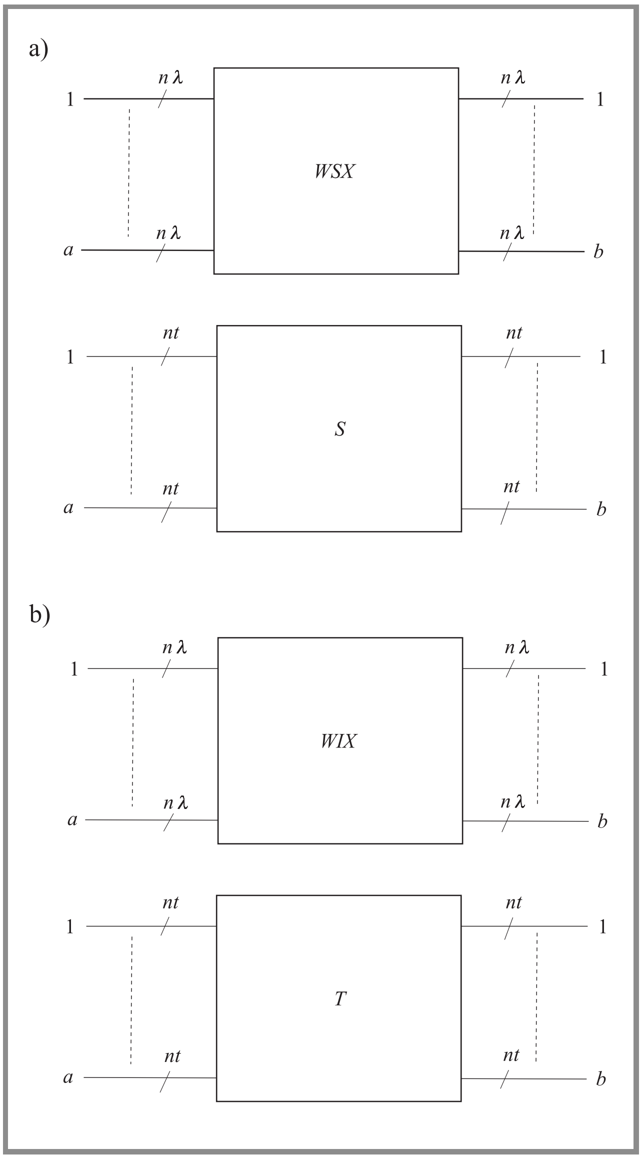

Fig. 4. Electronic equivalent of optical WSX (a) and WIX (b) matrices.

matrices we have only space connection between matrix input and output. The same situation can be observed for FX fiber matrix that connects input and output fiber and for that reason we can say that the analog space matrix is equivalent for fiber matrix. From this it results that the analog space switching network is an equivalent for GS_{FX} switching network (Conclusion 1).

Digital matrix is constructed based on time slot division multiplexing, however the optical matrix on wavelength division multiplexing. When we, for optical matrix, replace wavelength with time slot, then we obtain time slot division matrix as an equivalent. That replacing can be made for two types of optical matrix presented in the paper, WSX and WIX type of matrix. In the first one we obtain as an equivalent digital space matrix S with frame length equal to n and for that reason GS_{WSX} switching network has equivalent S-S-...-S-S switching network (Conclusion 2). For the second one the time switching matrix T is the equivalent matrix. These two cases are presented in Fig. 4. The *nt* symbol denotes n time slots in the frame.

The two, above described optical switching network constructions with WIX matrices, have two different equivalent electronic switching networks. For $GS_{WIX\_WSX\_WIX}$ the switching network structure the T-S-...-S-T structure is an equivalent however for $GS_{WIX\_WIX\_WIX}$ is the T-T-...-T-T structure.

The electronic S-S-...-S-S, T-S-...-S-T and T-S-...-S-T switching network structures are very well recognized and theoretically described [8, 9]. All these results can be transferred to the optical switching network.

Conclusion 5. Connection properties of above considered optical switching networks are the same as their electronic switching network equivalents and thus are very well described.

Only the theoretical results of optimalisation problems must be reformulated because of different criteria for optical and electronic switching networks. For the optical switching networks very important are the number of interstage links and the number of stages and the crosstalk [10], on the contrary to the electronic switching networks are the memory capacity and dimension of matrix.

We must emphasize that these optical switching networks because of limitation to switching in space (fiber) and wavelength do not cover all needs, which must be realized by switching function. These considered optical switching network constructions are transparent for flows aggregated in and transmitted by one wavelength. For the backbone network on the upper plane that will be done but not for the lower one. In the lower plane must be process of individual flows. This can be solved only when the optical switching function will be realized also in time not only in space and wavelength dimensions. Switching in time dimension can be realized in two ways, that is by assumption time or packet division multiplexing. But to meet this an appropriate optical matrix type must be designed.

5. Conclusions

In this paper connection properties of optical switching networks based on presented three types of matrices were analysed. Each of these optical matrices has an equivalent in the electronic domain. The multistage optical switching network constructed on these matrices type can be transformed into an electronic equivalent from the connection properties point of view. The four described main structures of two side optical switching networks have the same properties as the electronic switching networks. Wavelength is replaced by time slot by transformation from optical to electronic equivalent. All theoretical results for electronic space and time switching networks can be transferred to optical switching networks. Because of wavelength transparency, the optical switching networks can connect only aggregated streams in the wave. To have switching possibility of individual connections and streams transported by the wave, an optical matrix with time dimension must be designed.

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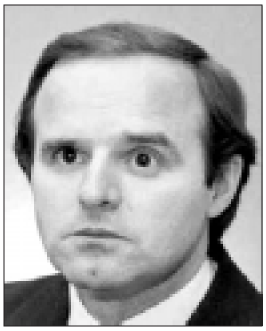

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