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Strict-sense nonblocking networks with k degrees of freedom

Wojciech Kabaciński*, Janusz Kleban, Marek Michalski, Mariusz Żal

Poznan University of Technology, Faculty of Electronics and Telecommunications, ul. Polanka 3, 60-965 Poznań, Poland

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ABSTRACT

In this paper we extended the well known conditions for strict-sense nonblocking operation of the three-stage Clos switching network to the case in which k multiplexing levels (called later in this paper as k degrees of freedom) are used on input, output, and interstage links. Up till now only the cases with one multiplexing level were considered in the literature—time-division or wavelength-division. Current research shows that transmission systems with many multiplexing levels will be used in the future to increase available transmission speed in telecommunication networks. There will be also a need for switching connecting paths going through such multiplexed links in large capacity optical cross-connect systems, routers, or data center networks. In this paper we proved the strict-sense nonblocking conditions for the three-stage Clos network with k degrees of freedom. We also analyzed the cost of switching fabrics of selected capacities and with three degrees of freedom in terms of the required number of elements.

1. Introduction

Three-stage switching networks were proposed by Clos [1] for space-division switching in telephone exchanges. Since that time they were a subject of many research papers; an interest in these networks was also changing in time. This interest depended on available technology and also transmission and switching methods used in a network. Clos' switching networks were extended to switching networks with time-division multiplexing [2] when digital switching matrices were introduced into the market. The three-stage switching networks (Clos or Beneš) were also used in many other node architectures like digital cross-connect systems, optical cross-connect systems or carrier-grade high capacity routers [3,4]. Currently the interest in Clos network topology is growing because of data center network architectures [5,6].

In the last years we observed the exponential growth of the Internet traffic, and such grow is expected in the near future. According to data presented by CISCO, the total IP traffic should reach 1.4 ZB by 2017 [7]. Devices like smart mobile terminals or tablets, progress in high-speed mobile access, and common access to broadband services (video on demand, IPTV, videoconferences, cloud computing) result not only in the increase of Internet traffic, but also in changes how services are available to users and how data are stored in a network. Currently web pages, films, music, pictures or other data are not stored on private storage devices or servers, but are located in big datacenters which contain tens and even hundreds of thousands of servers [9]. In White Papers [7,8] it is stated, that the volume of traffic inside data centers reached 3.8 ZB in 2014, and may reach 7.1 ZB in 2017 and 8.6 ZB in 2018. This increase of traffic requires networks of higher capacity than today's networks [10]. To meet the needs for higher network capacity, new transmission and multiplexing methods have been proposed. Time-Division Multiplexing (TDM) systems which were used in PDH and SDH transmission, and Wavelength-Division Multiplexing (WDM) systems are the systems which are now used in telecommunication networks. Moreover, both multiplexing methods are used simultaneously on optical links, i.e. TDM signals are transported on WDM channels. We may say, that two levels of multiplexing are used on a link. Currently, new multiplexing methods are at the different stage of research, experiments, or practical implementations, like Code-Division Multiplexing (CDM), Phase-Division Multiplexing or Mode-Division Multiplexing (MDM) [11–18]. We may also consider a Spatially-Division Multiplexing (SDM), since multi-core fibers may be considered as spatially multiplexed links [19,20]. Each multiplexing level is referred to as a level or a degree of freedom.

New multiplexing methods which are/will be used in transmission systems will impose new requirements on switching nodes. Switches which can switch TDM or WDM signals are available for a long time. Switching elements which will be able to

* Corresponding author.
E-mail addresses: wojciech.kabacinski@put.poznan.pl (W. Kabaciński), janusz.kleban@put.poznan.pl (J. Kleban), marek.michalski@put.poznan.pl (M. Michalski), mariusz.zal@put.poznan.pl (M. Żal).

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switch other multiplexed signals will appear in the future. In general, we may say that the system may have k degrees of freedom. For instance when in one fiber we have many cores, on each core we transmit signals in many wavelength, for each wavelength we use several modes and in each mode we use time-division multiplexing (it may be synchronous transmission like SDH or OTN frames or asynchronous transmission like IP packets), we may say that there are four multiplexing levels used in this link: space, wavelength, mode, and time (4 degrees of freedom).

We should also point out that in case there is no multiplexing system used in links, a switching fabric switches signals in the space domain only (space-division switching). When links with multi-core fibers are used, i.e., space-division multiplexing is used, a switching fabric also switches signals only in the space domain. In the later case, we have one multiplexing and one switching level. To be consistent with the terminology, when there is no SDM in links (single-core fibers are used) we consider such links as links with one multiplexing level which has only one multiplexing channel (one core in a fiber), i.e., $m_1 = 1$. This way, we can say that there is the same number of multiplexing and switching levels.

Switching fabrics with many multiplexing levels may be used in networks where a huge volume of data needs to be transferred between network elements. Examples of such systems are DCN (Data Center Network) or HPC (High Performance Computing). In order to ensure the required (high) performance, these systems must provide ultra-high throughput between servers, and at the same time guarantee very low latencies (which is especially important in the case of HPC, where parallel, interrelated computing tasks which are parts of a larger application, are run concurrently on multiple processors or servers). Unfortunately, DCN architectures that are currently commercially available, rely on the Ethernet protocol and electrical switches, which are traffic bottlenecks and sources of high latencies. Another disadvantage of such an architecture is a large power consumption [21,22]. The possible solution to reduce the power consumption is to use optical packet switching (OPS) with an all-optical data plane. But such a solution also has a serious disadvantage, i.e., it is not mature yet and cannot be used in practical networks. Of course, there are a few existing implementations, such as LIONS [23,24], Petabit [25], IRIS [26], Data Vortex [27], but all of them exist only as prototypes. Some of the mentioned projects are based on SOAs as switching elements, which are considered fast, but generally the switching time of optical switching elements is also insufficient to be used in optical packet switching with current optical link transmission speed. Instead of OPS, a new approach is to use optical circuit switching (OCS) in parallel with electronic packet switching (EPS) to create a hybrid data transmission network. Such hybrid EPS/OCS DCN architectures are presented in [28,29]. The implementation of OCS based on switching fabrics with many multiplexing levels may solve another critical problem of DCN, as it reduces the huge number of links.

The three-stage space-division switching networks were firstly considered by C. Clos [1] who proved the strict-sense nonblocking conditions. Three-stage switching networks with time-division multiplexing on links and with time-division switching were presented in [2], and strict-sense nonblocking conditions for such networks were proved in [30]. Another example are networks with wavelength-division multiplexing. They may be implemented using optical switches. Their nonblocking conditions were considered in [31,32]. A survey of different combinatorial properties of Clos networks, not only strict-sense nonblocking, but also wide-sense nonblocking and rearrangeable, can be found in [33–35]. As far as we know, up till now, operation of the Clos network was considered only for one degree of freedom, i.e., one multiplexing level was used on links (time or wavelength). Recently, we considered a switching fabric with three multiplexing levels (SDM, WDM, and MDM) used on links, where the number of channels on the SDM level was limited to 1 [36].

In this paper, we extend the results presented in [36] to a case with k degrees of freedom. Moreover, we assume that switches between stages may be connected with more than one interstage link (so called ν-dilated switching fabrics). We also present more detailed numerical examples and the optimization of the proposed switching fabrics. We discuss architectures not only with the lowest numbers of crosspoints, but also with the lowest numbers of converters in each multiplexing level. Some cost analysis is also made for a network with different costs of converters and switching points. The formulas and results proved in this paper can be further used for designing the optimal structures of switching fabrics, for instance for high-performance datacenter networks or optical switching nodes. We also present examples of such optimization. The rest of the paper is organized as follows. In Section 2 we describe the general switch architecture and notation used in the paper. In Section 3 conditions for strict-sense nonblocking operation of the switching fabric are derived and proved. In Section 4 we consider the problem of optimizing switching fabrics with k degrees of freedom. We also present several optimized structures, optimization of which was performed according to selected criteria. Section 5 concludes the work.

2. The switch and switching fabric architectures

Let us present the switch operation and the three-stage switching fabric architecture which will be considered in this paper. Since many multiplexing technologies may be used at the same time in transmission links, we assume that k degrees of freedom are available in the switch. The general idea of the switch considered in this paper is presented in Fig. 1. It contains n input and n output fibers, numbered from 1 to n. In each fiber k multiplexing methods denoted by M^i, $i = 1 \dots k$, are used. In each multiplexing method M^i the number of available channels is denoted by m_i. For each multiplexing method, channel j of method M^i, $1 \le j \le m_i$, $1 \le i \le k$, is denoted by M_j^i. The whole link partitioned into logical channels by k multiplexing methods is shown in Fig. 2. For instance, let us consider a link in which WDM, MDM, and TDM systems are used. These systems correspond to multiplexing methods M^1, M^2, and M^3, respectively. In the WDM system there are m_1 wavelengths. On each wavelength Mode-Division Multiplexing is used with m_2 modes, and on each mode TDM system is used with $m_k = m_3$ time slots. In the link presented in Fig. 2 each channel on the lowest level multiplexing systems, i.e. M^k, will be called as a logical channel or simply a channel. We have $\prod_{i=1}^{k} m_i$ such channels. In the link with WDM, MDM, and TDM systems considered as an example we have $m_1 {*} m_2 {*} m_3$ channels (time slots).

In the switch of Fig. 1, any input channel can be switched to any of the output channels. We call this switch as the switch with k degrees of freedom, since we can switch signals between k multiplexing systems. Possible functional architecture of such switch is shown in Fig. 3. At the input side, signals from input fibers are demultiplexed level by level until channels are separated in

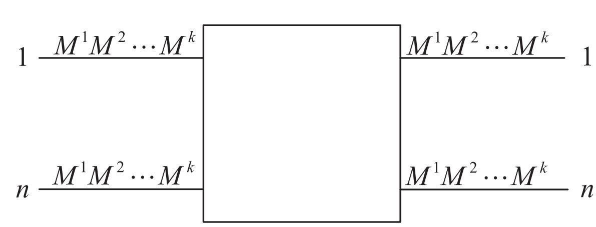

Fig. 1. A switch with k multiplexing levels on input and output links.