QoS Criteria for Energy-Aware Switching Networks

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Abstract. This article proposes a method to determine the QoS parameters for energy-aware multiservice switching networks. The initial assumption is that a decrease in the power uptake by the network can be achieved by a temporary switch-off of a certain number of switches. To this end, the article develops methods for a determination of the blocking probability in switching networks with a variable number of switches. The results of the analytical calculations are then compared with the results of simulation experiments for a selected number of structures of switching networks. The study reveals the good accuracy of the proposed model. The results obtained in the study can be applied in constructing energy-aware switching networks.

Keywords: Switching network · Multiservice traffic · Energy-aware systems

1 Introduction

Works on network energy demand have been carried out at a number of levels: from the lowest one, involving the construction of devices, through the improvement of algorithms that control the operation of individual interfaces, up to the highest level related to dimensioning and designing of networks and systems. It is plain to see that the power consumption of network devices largely depends on the volume of offered traffic [2,28]. While choosing appropriate devices, network operators target economic efficiency and service quality and rely on and are guided by the maximum traffic value in those periods that are deemed to provide the heaviest load for systems. This, in turn, leads to the application of "over-dimensioned" devices throughout most of the 24-hour working time. In such circumstances, a temporary switch-off of certain elements in network devices or, should the need arise some of their modules, seems to be an appropriate solution to the problem [15].

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Works on optimization of the operation of network nodes in relation to the minimization criterion for power consumption have been conducted in a large number of company research centers and academic institutions, e.g. [5,12,15,18,27–29]. One of the possibilities to minimize energy uptake is to apply appropriate traffic engineering algorithms [2,15,28]. More and more often, connections between servers in data centers have topologies that correspond to the structures of switching networks (SN). Within this particular context, an application of appropriately selected algorithms can lead to a decrease in the demand for energy in data centers [5,12,18].

This article discusses the emerging possibilities that can be exploited to design optimum energy-aware SNs. A construction of such networks is based on the two following criteria: minimization of power uptake and minimization of the blocking probability. The former criterion can be satisfied by utilization of appropriate mechanisms for deactivation of individual elements of a SN during network low-load periods. This means that a certain number of the elements of a SN (e.g. switches) will be temporarily "removed" from the network structure. However, the two above mentioned criteria contradict each other – switching off of certain elements causes the blocking probability to be increased. Therefore, the optimization process should be intertwined with a certain assumed and pre-defined boundary level for the Quality of Service (QoS) parameters.

The SN analysis is based on effective availability models. This concept is proposed for two-stage single-service SNs in [1,3] and then generalized to include any number of stages [6,17,25]. A number of effective availability models are also proposed for multiservice SNs [8,23,26]. The literature of the subject also offers models that expand the range of possible applications of effective availability methods, e.g. [7,9–11,13,24].

This article discusses a possibility of a determination of boundary QoS parameters for energy-aware SNs. The influence of changes in the SN structure on the blocking probability of individual traffic classes is then determined. For this purpose, an appropriately modified Point to Group Blocking for Multichannel Traffic (PGBMT) method for a SN operating in the point-to-group selection mode [23,26] is used. In the proposed model, the blocking probability for successive SN structures in which the number of switches is decreased is determined. The obtained results can be applied to construct energy-aware SNs structures that would satisfy the adopted QoS assumptions. The present article is structured as follows. Section 2 provides a description of a Clos multiservice SN. Section 3 includes a discussion of an analytical model of a multiservice switching network in which the number of switches of the middle stage is variable. In Sect. 4, the results of the analytical calculations are compared with the results of the simulation experiments. Section 5 sums up the article.

2 Multiservice Switching Network

Figure 1 shows the structure of a three-stage Clos SN [4,30]. Each stage of the SN has k symmetrical switches with $k \times k$ links. All links have the capacity equal

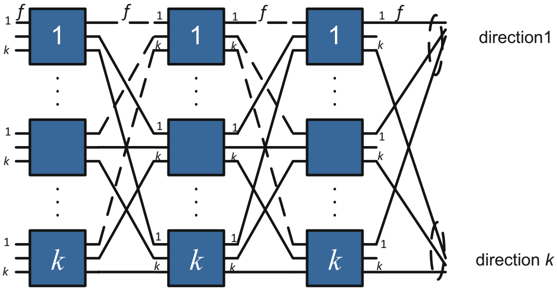

Fig. 1. Three-stage Clos switching network

to f Allocation Units (AUs). A single AU is expressed in kbps and is defined as the Greatest Common Divisor (GCD) of bitrates of all traffic classes [19,21]. The output links of the SN form the so-called output directions. The assumption is that the i-th output links of each of the switches of the last stage create an i-th direction.

If a switch of the middle stage, for example the first switch in Fig. 1, is removed from the network, then all links that connect this switch with the switches of the neighboring (adjacent) switches (marked by the dotted line in Fig. 1) will also be removed. Therefore, if we remove u switches of the middle stage from the network structure, we will obtain a network comprised of k switches of the type $k \times (k-u)$ in the first stage, $(k-u)$ switches of the type $k \times k$ in the second stage and k switches of the type $(k-u) \times k$ in the third stage. The initial assumption is that traffic offered to the SN is a mixture M of Erlang traffic streams that can be characterized by the following parameters: A_i – the average intensity of traffic of class i $(1 \leq i \leq M)$ offered to links of the switching network, t_i – the number of AUs $(1 \leq t_i \leq f)$ required for a connection of class i in the SN to be set up.

A further assumption is that the SN operates in the point-to-group selection mode. The control algorithm determines first a switch of the first stage at the input of which a new call has arrived. Then, the algorithm determines the switches of the last stage that have free outputs in the demanded direction. If all links of a given direction are occupied (busy), then the phenomenon of internal blocking will occur and the call will be discarded and lost. If even one link of a given direction is free, then the algorithm will attempt to set up a connection between the switch of the first stage that has been determined earlier and a switch of the last stage that has a free output in the demanded direction. If the execution of the connection is not possible, the algorithm will check successively a possibility of setting up a connection with other switches of the last stage that have free links in the given direction. If setting up of a connection is still impossible, then the call will be lost due to the phenomenon of internal blocking. Note that in the case of multiservice switching networks, the notion of a free link for calls of class i means that this link has at least t_i free (unoccupied) AUs.

3 A Model of the Switching Network with Variable Network Structure

The modified version of PGBMT method was used in the paper to model multiservice SNs with a variable number of switches in the middle stage [23]. The idea behind the method is based on a determination of a fictitious non-full-availability system in which the blocking probability for calls of individual classes is exactly the same as in the SN. The accompanying assumption is that traffic offered to the fictitious system and to a given direction of the network is identical. The fictitious system is indicated by the availability parameter. In the PGBMT method, the value of the availability for particular traffic classes, called effective availability, can be determined on the basis of the structure and load of the SN. The method is composed of the following elements: a model of inter-stage links, model of output links and a method to determine effective availability for each of traffic classes. These three elements enable us to determine the blocking probability for call streams that are offered in the SN. In this section, a method for a determination of effective availability for a variable number of switches of the middle stage is proposed.

3.1 Model of Inter-stage Links

A full-availability group (FAG) with multiservice traffic [14,20] can serve as a model of inter-stage links. The group has the capacity f AUs. The occupancy distribution $[P_n]_f$ and the blocking probability $E_{i,\mathrm{FAG}}$ for calls of class i in a link with the capacity f AUs can be described as follows:

$$n\,[P_n]_f = \sum\nolimits_{i=1}^{M} A_{i,\mathrm{FAG}} t_i\,[P_{n-t_i}]_f\,, \tag{1}$$

$$E_{i,\mathrm{FAG}} = \sum\nolimits_{n=f-t_i+1}^{f} [P_n]_f\,, \tag{2}$$

where n is the number of busy AUs in the FAG with the capacity f AUs and $A_{i,\mathrm{FAG}}$ is the intensity of traffic of class i offered to the FAG. If A_i is the intensity of traffic of class i, whereas u is the number of removed switches of the middle stage, then in symmetry strength of the SN from Fig. 1 we can write:

$$A_{i,\mathrm{FAG}} = A_i / \left[k(k-u)\right]. \tag{3}$$

3.2 Model of Output Links

The output group (direction) of the SN from Fig. 1 comprises of k links with the capacity f AUs. To model the direction, a limited-availability group (LAG) can be used [22]. The group is composed of k separated links. The concept of separation results from the underlined method of service. A call of class i can be serviced only when the LAG has at least t_i free AUs in a single link. This means that a call cannot be "divided" between AUs of a number of links. This method for service corresponds to the operation of SNs, where each call is always serviced by only one link in a given direction. The occupancy distribution $[P_n]_V$ in a LAG with the capacity $V = kf$ can be then expressed by the following formula:

$$n\,[P_n]_V = \sum\nolimits_{i=1}^{M} A_{i,\mathrm{LAG}} t_i \omega_i(n - t_i)\,[P_{n-t_i}]_V\,, \tag{4}$$

where $A_{i,\mathrm{LAG}}$ is the intensity of traffic of class i offered to a given direction:

$$A_{i,\mathrm{LAG}} = A_i/\,k. \tag{5}$$

The parameter $\omega_i(n)$ in (4) is the conditional transition probability between states n and $(n+t_i)$. The parameter determines the probability of such a distribution of free AUs in the LAG that makes service of a call of class i in state n possible:

$$\omega_i(n) = [F(V-n,k,f,0) - F(V-n,k,t_i-1,0)]/\,[F(V-n,k,f,0)]. \tag{6}$$

The combinatorial function $F(x,k,f,h)$ determines the number of arrangements of x elements (free AUs) in k sets (LAG links), each with the capacity f elements (AUs). The assumption is that in each set h elements have been earlier deployed (accommodated):

$$F(x,k,f,h) = \sum_{g=0}^{\lfloor \frac{x-kh}{f-t+1} \rfloor} (-1)^g \binom{k}{g} \binom{x-k(h-1)-1-g(f-h+1)}{k-1}. \tag{7}$$

On the basis of (4), the distribution of free links $[P_s(i)]_k$ can be derived. This distribution determines the probability that s links can serve a call of class i [22]:

$$[P_s(i)]_k = \sum_{n=0}^{V=kf} \frac{\binom{k}{s} \sum_{z=st_i}^{\Psi} F(z,s,f,t_i) F(V-n-z\,k-s,t_i-1,0)}{F(V-n,k,f,0)}\,[P_n]_V\,, \tag{8}$$

where $\Psi = sf$ for $n \leq V - sf$ and $\Psi = V - n$ for $n > V - sf$. Note that for $s = 0$, the probability $[P_0(i)]_k$ determines the blocking probability for calls of class i in the LAG.

3.3 Blocking Probability in Switching Networks

In the PGBMT method, the internal blocking probability $[E_{\mathrm{int}}(i)]_{\mathrm{SN}}$ for traffic of class i in the multiservice SN is defined by the following formula:

$$[E_{\mathrm{int}}(i)]_{\mathrm{SN}} = \sum_{s=1}^{k-d(i)} \frac{[P_s(i)]_k}{1-[P_0(i)]_k} \left\{ \binom{k-s}{d(i)} \Big/ \binom{k}{d(i)} \right\}, \tag{9}$$

where $d(i)$ is the effective availability for calls of class i (Sect. 3.4). Formula (9) determines the probability that all $d(i)$ available switches of the last stage have occupied links in a given direction. In (9), a truncated distribution $[P_s(i)]_k/(1-[P_0(i)]_k)$ of free links is used because the event of internal blocking occurs exclusively in the case of the existence of at least one free link in a given direction. Therefore, a situation in which all links in a given direction are occupied must be excluded. To determine the external blocking probability $\left[E_{\text{ext}(i)}\right]_{\text{SN}}$ for calls of class i the distribution $\left[P_s(i)\right]_k$ is used:

$$\left[E_{\text{ext}}(i)\right]_{\text{SN}} = \left[P_0(i)\right]_k . \tag{10}$$

The control algorithm first checks the existence of free links in a given direction, i.e. checks whether the phenomenon of external blocking occurs or not. If not, then the algorithm attempts to set up a connecting path in the SN. Taking, therefore, into account the operation of the algorithm, the total blocking probability in the SN is the sum of the external blocking probability and the internal blocking probability, with the exclusion of a possibility of a concurrent occurrence of the event of external and internal blocking:

$$\left[E(i)\right]_{\text{SN}} = \left[E_{\text{ext}}(i)\right]_{\text{SN}} + \left[E_{\text{int}}(i)\right]_{\text{SN}} \cdot \left[1 - \left[E_{\text{ext}}(i)\right]_{\text{SN}}\right] . \tag{11}$$

3.4 Effective Availability for Calls of Class i

The PGBMT method is based on reducing a multi-stage SN to a fictitious single-stage system, the so-called non-full availability group, characterized by the effective availability parameter. The parameter is defined as such an availability to switches of the last stage for which blocking probabilities in the SN and the non-full availability are identical. Effective availability for a given call class can be determined on the basis of the so-called equivalent network (EN) that has the same structure as the SN, but the capacity of the links equal to 1AU. While making a determination of the effective availability for a given traffic class the assumption is then that the EN services only this class and the load of each of the links in the EN is equal to the blocking probability of a given class of calls in a SN link. Effective availability for traffic of class i in a three-stage SN can be determined by the following formula [23]:

$$d_u(i) = \left[1 - \pi_u(i)\right] k + \pi_u(i) b(i) \left\{1 + \left[k - a_u(i)\right]\left[1 - a_u(i)\right]\right\} , \tag{12}$$

where:

- $\pi_u(i)$ – the probability of unavailability of one switch of the third stage in SN in which u switches of the middle stage have been removed,
- $a_u(i)$ – fictitious load of EN link for calls of class i, determined on the basis of the FAG model (Formulas (1)–(3)):

$$a_u(i) = E_{i,\text{FAG}}, \tag{13}$$

- $b(i)$ – fictitious load at the EN output. This parameter is determined by Formulas (1)–(3), with taking into account the fact that the number of links in a given direction is fixed (constant) and does not depend on removed switches of the middle stage taken into consideration. Hence, in (3) the assumption should be that $u = 0$.

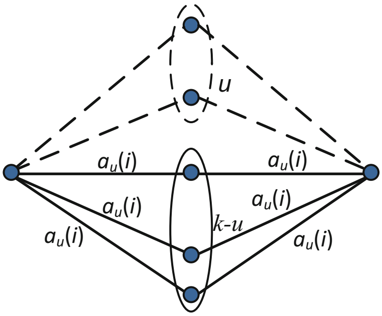

Fig. 2. Channel graph of the three-stage switching network from Fig. 1

The parameter $\pi_u(i)$ can be determined on the basis of an EN channel graph that shows all possible connecting paths between the switches of the external stages. Figure 2 shows the SN channel graph from Fig. 1. Each of its edges is attributed the fictitious load $a_u(i)$. The probability $\pi_u(i)$ corresponds to the blocking of all connecting paths and can be determined on the basis of the method [16]. For the graph from Fig. 2, in which u switches of the middle stage have been removed, we then have:

$$\pi_u(i) = \left\{1 - [1 - a_u(i)]^2\right\}^{k-u}. \tag{14}$$

In Formula (14), the expression $1 - a_u(i)$ means that the graph edge is free, therefore $1 - [1 - a_u(i)]^2$ determines an event of blocking of a connecting path. By raising this expression to the power $(k - u)$ we can determine the blocking events for all connecting paths.

3.5 Commentary

A possibility of changing the SN structure, which consists in a temporary deactivation of a certain number of switches, is assumed in works on energy-aware SNs. This process is correlative with a pre-defined boundary level of blocking. This means that in any circumstances and under any conditions the SN structure can be changed in such a way as to prevent the blocking probability from exceeding the required values. The proposed modification to the PGBMT method maps any changes in the SN structure into changes in the value of the effective availability parameter. As a result, the method allows boundary blocking probabilities for particular call classes for a variable number of switches of the middle stage of a three-stage Clos SN to be evaluated.

4 Numerical Examples

The proposed model of a multiservice SN with a variable number of switches of the middle stage is an approximate model. To determine its applicability for

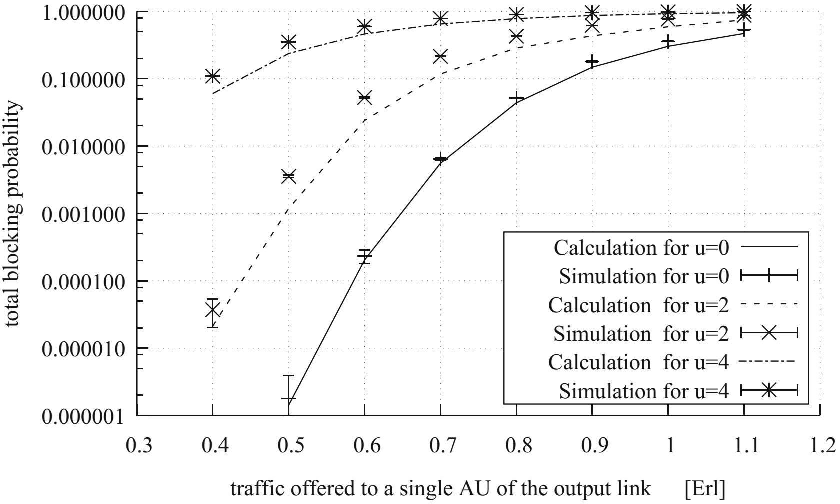

Fig. 3. Blocking probability for class 3 calls ($t_3 = 6$ AUs) in the switching networks with variable number of active switches in the middle stage

modeling energy-aware networks, the results of the analytical calculations were compared with the results of the simulations for a selected number of Clos SNs (Fig. 1). A network with the following parameters was chosen for modeling:

- size of the switch of the first stage: $8 \times (8 - u)$,
- size of the switch of the second stage: 8×8,
- size of the switch of the third stage: $(8 - u) \times 8$,
- capacity of the input, output and inter-stage link $f = 30$ AUs,
- the number of classes of offered traffic $M = 3$,
- the demanded number of AUs for offered traffic classes: $t_1 = 1$ AU, $t_2 = 2$ AUs, $t_3 = 6$ AUs,
- proportions of the offered traffic mixture: $A_1t_1 : A_2t_2 : A_3t_3 = 1 : 1 : 1$.

Figure 3 shows the results of the modeling of the SN under consideration for the number of switches of the middle stage equal to 8 ($u = 0$), 6 ($u = 2$) and 4 ($u = 4$). Due to the limited length of the paper, the results for the class with the maximum demands are only presented. The results of the simulations are shown in the form of points with 95 % confidence intervals determined on the basis of the t-Student distribution for 10 series with 10000000 calls of each class in each series. The results of the analytical modeling are presented in the form of lines.

The results obtained in the study reveal good accuracy of the proposed SN model with a variable number of switches in the middle stage. All the results are expressed in relation to the value of traffic offered to one AU of the output link in SN:

$$a_{\text{out}} = \sum\nolimits_{i=1}^{M} [A_i t_i]/k^2. \tag{15}$$

Let us assume that the acceptable value of the blocking probability is 5%. While analyzing the results presented in Fig. 3 one can observe that with a decrease in the value a_{out} from 0.8 Erl./AU to the level of 0.6 Erl./AU it is feasible to use a SN with 6 switches in the middle stage, instead of 8 switches, in order to keep the assumed value of blocking.

5 Conclusions

This article proposes a new method to model multiservice SNs with a variable structure that allows the number of switches of the middle stage of an SN to be decreased. The application of a variable load-dependent structure makes it possible to construct energy-aware networks. The present article does not discuss the issue of constructing such SNs. What the article is focused on is to show how and in what way a change in the structure of a SN can influence the blocking probability for individual traffic classes. As a result, the method proposed in the article can be used in practice to help solve designing and optimization issues with regard to constructing energy saving algorithms by way of limiting the number of active elements to values that secure acceptable level of the QoS parameters.

The intention of the authors is to pursue the work initiated in the article and to develop, on the basis of the proposed method, appropriate algorithms for temporary activation/deactivation of a certain number of switches, which in consequence will allow a lowered power consumption by a switching network to be quantitatively estimated. In the further works, in order to increase the accuracy of the model, blocking probability phenomenon of the first stage switches will be incorporated to the model.

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