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DYNAMIC INTERNATIONAL OPTICAL NETWORK BY FUZZY ROUTING

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Abstract: Optical communications transmit large amount of data, operating from local to transoceanic distances. Wave division multiplexing WDM is crucial point for achieving reliable real-time data transmission over precise fiber-optic cables and nodes technology. This paper brings novel method for optical links evaluation used for optimal path finding when data transmitting over dynamically loaded international optical network. Middle-European NRENs and pan-European GÉANT are implemented to the simulation model. For efficient links' assessment, several parameters are taken into account. They are employed by fuzzy logic subsystem to estimate their relationships and, each link quality and utilization judgment. Composed simulation model demonstrates routing (i.e. path finding) flexibility and utilization balancing over existing optical links.
Keywords: fuzzy routing, dynamic optical network

INTRODUCTION

Optical networks provide node-to-node connections over long distances. Routing in wavelength division multiplex (WDM) optical networks has been widely discussed for different types of optical networks. Current approaches and solutions are based on an output parameter evaluation, mostly eye diagram (Q-factor) or, power and spectrum dissipation.

In WDM systems, optical bandwidth is met by employing multiple carrier wavelength channels over a fiber. It respects transmission limits [1], depending on route components [2], modulation methods, transport protocols, operational modes and wavelength routing control abilities. Dynamic flexible control approaches bring better bandwidth agility [3-9]. The most used routing and wavelength assignment algorithms implement various methods to improve overall throughput: a shortest path choosing within user-specified or network-specified constraints, alternate routing creation, etc.

Modern optical network systems embrace highly sophisticated automated processes to improve overall throughput. They apply numbers of methods for optimal re-routing, advanced modulations [10], [11], wavelength optimization [7], [9], [12-16], backup linking etc. Cognitive light path optimization by OSNR may be used, [17], [18]. Of course, such an important parameter must be considered during fiber optics planning process [19], [20]. Fuzzy controlled mesh networks can provide functions like fuzzy-measures defined wavelength reconfiguration [5], [8], [21], routes updating [22] and utilization balancing, even close to transmission limits.

This paper focuses on data transmission routing optimization in WDM optical network. Data transmission is considered via several transfer nodes and paths, deliberating the path parameters triplet: optical signal-to-noise ratio (OSNR), bit error rate (BER) and output power (Power). Near future links' status is estimated over real network.

The paper illustrates data routing process by implemented fuzzy logic, statistical evaluation and decision processing methods. Not only is the proposed system applicable to solve re-routing when data traffic demand increase during peak traffic hours, but also it meets degradation factors impact etc.

GÉANT NETWORK

GÉANT, the pan-European and worldwide data network, interconnects research, education and innovation communities, with secure, high-bandwidth and high-capacity networks.

It spans over 50,000 km and connects over 50 million users, including 38 European National Research and Education Networks (NRENs). As from [23], the GÉANT topology covers most European countries yet, providing high-speed interconnection at 1-9 Gbps, multiples of 10 Gbps or multiples of 100 Gbps. In the simulations, a simplified topology is composed, Figure 1, comprising middle-European plus neighboring countries GÉANT links between them.

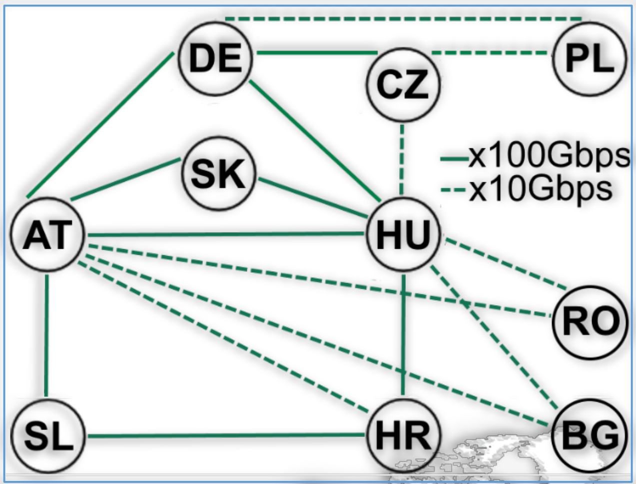

Figure 1. Simplified middle-European GÉANT interconnections

NRENs

A NREN represents an internet service provider dedicated to support research and education communities in a country. A NREN is usually distinguished by support for a high-speed backbone network, often offering dedicated channels for individual research projects. Often, many services, internet data transfer protocols, applications etc. are available. [24]

In this manner, overall transport capacity continuously increases in accordance with the needs and real traffic through the individual nodes. Thus, each of NRENs owns or rents backbone network at different speed, technology and geographically-dependent structure. Backbone networks mostly interconnect universities, academic and research institutions.

As a GÉANT members, NRENs dispose of cross-border backbone interconnections. Besides, some neighboring NRENs apply direct interconnection by extra optical fiber.

A brief overview of current NRENs deployed in middle-European region is provided in this section, due to papers' focus on GÉANT plus NRENs gained from their territorial cooperating effect. As presented in the next subsections, cross-border links usually provide speed of multiples of 10 Gbps.

The simplified model in Figure 2 represents cross-border direct links between middle-European and neighboring NRENs. These are introduced below.

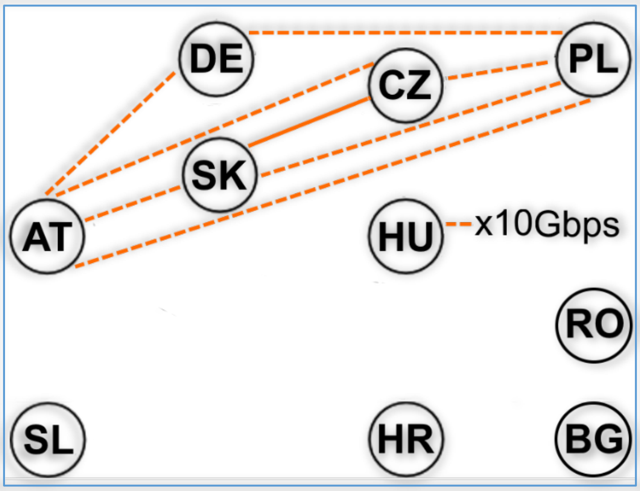

Figure 2. Simplified middle-European NRENs interconnections

A. DFN - Germany

The German (DE) Deutsches ForschungNetz (DFN) is a national backbone network for science, research and education. It connects German universities and research institutions by up to 100 Gbps and a multi-Tbps core network, spanning about 60 core location sites.

Functionality of Dense Wavelength Division Multiplex (DWDM) infrastructure and Quality of Services (QoS) is supervised by eight fundamental measurement sites connected mostly in triangle structure corners. Comprising about 10,000 km dark optical fibre in several rings, it is one of the most powerful communication network in the world.

The fibre platform is connected to GÉANT in Frankfurt as well as to neighboring NRENs by super core fibres with upstream speed of 10 Gbps. [25]

B. CESNET - Czech Republic

The core of the Czech (CZ) Education and Scientific NETwork (CESNET) is formed by DWDM infrastructure with tens of 100 Gbps, 10 Gbps, and small amount of 1 Gbps transmission channels. A combination of commercial devices and optical elements of own design (the CzechLight series) is used. The speed of network core was upgraded to 100 Gbps in 2013.

Other backbone circuits are based on the 100 Gbps, 10 Gbps and Gigabit Ethernet and the POS (Packet over SONET) technology with at the speed of 2.5 Gbps. The network topology consists of several rings connecting limited number of sites (optimally less than five city sites in a single ring).

The CESNET offers international connectivity, too. Individual 10 Gbps cross-border optical fibers cooperate with neighboring NRENs SANET (Slovakia), ACONET (Austria), PIONIER (Poland). Other optical interconnections operate directly to Netherland, USA, Google, each at speed of 10 Gbps. [26]

C. PIONIER - Poland

The Polish (PL) Optical Internet PIONIER NREN connects 21 Academic Network Centers of Metropolitan Area Networks (MANs) and 5 High Performance Computing (HPC) centers with own fiber connections spread about 6,000 km. MANs operate dark optical fibre at the data speed of 2x10 Gbps with DWDM technology.

There are 80 separate fibre pair channels between MANs as well as cross-border links. Cross-border connections lead to GÉANT, to Germany (continuing to GLIF, Surfnet and Nordunet), DFN (Germany, three nodes), CESNET (Czech Republic), SANET (Slovakia), UARNET and URAN (Ukraine), Belarus, Lithuania and Russia. [27]

D. ACOnet - Austria

The Austrian (AT) Academic COmputer NETwork (ACOnet) backbone provides a powerful network infrastructure among 12 locations connected in a redundant manner (six of locations are doubled sites thus there are 18 points of presence), to provide a stable and failsafe network.

ACOnet operates 10 Gbps Ethernet backbone network and transparent fiber optic internet with DWDM technology at speed of multi-10 Gbps. Cross-border fiber optic links lead to GÉANT, CESNET (Czech Republic), SANET (Slovak Republic) and PIONIER (Poland). [28]

E. SANET – Slovak Republic

The Slovak (SK) Academic NETwork SANET connects 13 western academic sites in a ring structure and four eastern academic sites in a line structure, all operating at the backbone data speed of multi-100 Gbps. Other 20 sites are arranged in a ring or line structures at the data speed of 10 Gbps. SANET general two-ring structure provides full redundancy. The network infrastructure is based on leased dark fibers terminated by Cisco Catalyst switches. The national connectivity is realized by Slovak Peering Center SIX. The cross-border connectivity is achieved by leased dark fibre at the speed of 20 Gbps to ACOnet (Austria), CESNET (Czech Republic), and 10 Gbps to PIONIER (Poland) and GÉANT. [29]

F. NIIF - Hungary

The Hungarian (HU) Nemzeti Információs Infrastruktúra Fejlesztési Intézet (NIIFI) and HUNGARNET association of its users fulfil role of NREN. The NIIFI/HUNGARNET backbone HBONE+ based on dark fibre optics with DWDM systems consists of robust core and regional centre routers connected to core routers (directly or indirectly).

There are 13 rings in meshed network structure, connecting 28 regional centers by 9 NIIFI sites. The HBONE+ main country links, Budapest links and international links operate 10, 40 or 100 wavelength channels per each of optical fibre, each channel achieving speed of 10 Gbps. Only small amount of local link connections achieve the data speed about 1 Gbps. The cross-border connectivity is enabled by the GÉANT at the data speed of 30 Gbps. [30]

G. ARNES - Slovenia

The Slovenian (SL) Academic and Research Network of Slovenia (ARNES) supports research and education communities. Next, it fulfils additional internet connection role for other commercial users essential to the operation of the Internet of Slovenia.

NREN structure creates Ljubljana – centered loops. Based on leased optical fibres with hybrid DWDM or Coarse WDM (CWDM) systems, the technology supports four 1 Gbps or sixteen 10 Gbps simultaneous data transmissions within an Ethernet point-to-point connections. The cross-border connectivity is enabled by the GÉANT at the data speed of 30 Gbps. [31]

H. CARNet - Croatia

The Croatian (HR) Academic and Research NETwork uses cables leased from telecommunication providers. The largest university centers operate high-speed connections at 155 Mbps to 1 Gbps while smaller centers operate at the speed of 2 Mbps to 200 Mbps.

Local institutional networks in two biggest centers operate at higher speeds using optical cables technology. NREN connections lead in star-centered shapes from three most important centers. The cross-border connectivity is enabled by the GÉANT at the data speed of 10 Gbps. [32]

I. RoEduNet - Romania

The ROmanian (RO) EDUcational NETwork is administrated by the Agency for Administration of the National IT Network for Education and Research (AARNIEC). It offers high-speed connections for 7 largest university centers and 34 points of presence. The cross-border connectivity is enabled by the GÉANT to Austria and Hungaria, each at the data speed of 10 Gbps. [33]

J. BREN - Bulgaria

The Bulgarian (BG) Research and Educational Network offers 1 Gbps connections to largest university centers via 13 backbone switches: Ethernet over SDH, dark fibre optics or MAN in Sophia. Some institutions are connected via 100 Mbps MAN. The cross-border connectivity is enabled by the GÉANT at the data speed of 10 Gbps. [34]

MERGED NETWORK MODEL

At the beginning of simulations, the topology of the main network is created, comprising principal nodes and links between them. Corresponding link speeds are set to multiples of 10 Gbps by NRENs and 100 Gbps by GÉANT links. The map merges cross-border links of both GÉANT and NRENs, see Figure 3. Here, some nodes are connected by several links (combination of GÉANT + NRENs). A link represents the shortest connection between two neighboring nodes, containing at least one fiber. A path is the connection between starting and output nodes, comprising one or more links.

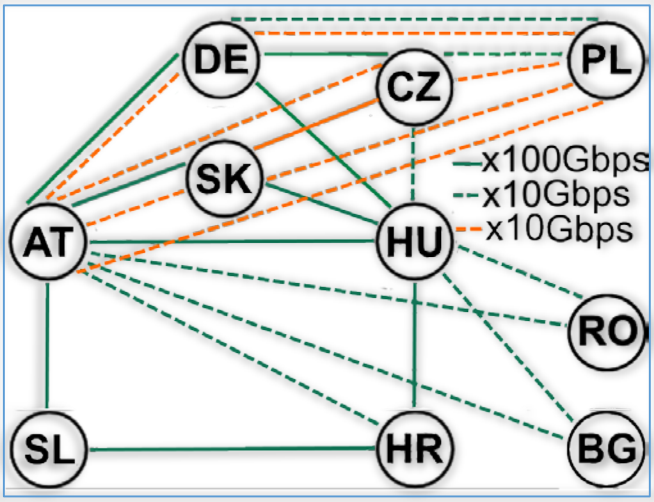

Figure 3. Network model comprising GÉANT and NRENs interconnections

All above mentioned link speeds represent their theoretical maximum capacity. In real data transmission conditions, external influences decrease this parameter. When simulating data routing in the merged network model, following link parameters triplet is considered:

K. Optical Signal – to – Noise Ratio (OSNR)

The *OSNR* is measured in each of data channel by an optical spectrum analyzer, comparing channel output power during non- active and active intervals.

L. Bit Error Rate (BER)

Data loss is mostly caused by signal loss / damping, frequency bandwidth changes, inter-channel interferences, or link-degradation processes.

Depending on channel coding methods, BER measurement, error detection, correction algorithms or automatic data repeating are performed at the binary channel output to improve channel quality.

M. Output Power (Power)

The channel optical power dissipation (at wavelength, per cable longitude) is caused by damping characteristics of the link, optical signal spectrum dispersion, channel power matching, amplification setup, link-degradation processes etc.

Dispersion compensation methods are used to reduce such optical power loss. The Power parameter defines signal power level at the link output terminal.

NETWORK CONTROL SYSTEM

Merged network control system processes OSNR, BER and Power triplet parameters' values, for each of modeled links, see Figure 4. However, the next two more link parameters must be entered when simulating real rooting in merged network model:

i. the maximum capacity (or wavelength channels) that represents the maximum transmission speed of a link (Gbps, see previous paragraphs),

ii. the current utilization that represents current link exploitation (in percentage). Simulation output parameter, a link (or wavelength channels) quality Q, is calculated for each link by fuzzy logic subsystem, using predefined fuzzy rules. For given link, the Q parameter represents weighted probability of near-future reliable data transmission (in percentage).

After obtaining Q, control system produces output cost for each link and available capacity $C_{available}$ of a link, by Equation 1.

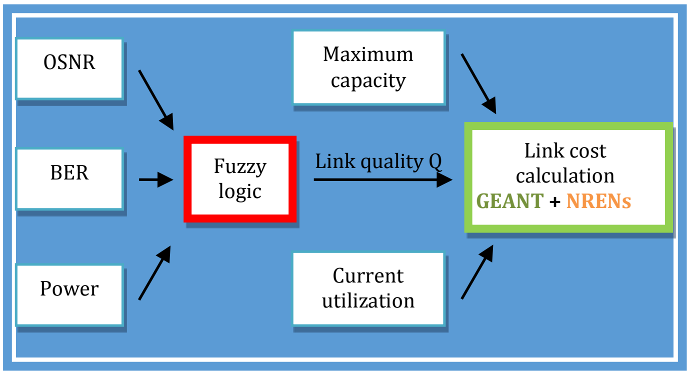

Figure 4. Link cost calculation algorithm

$$C_{available} = C_{max} * (1 - U) * Q \qquad (1)$$

where:

» $C_{available}$ is available link transport capacity [Gbps],
» C_{max} is maximum link capacity [Gbps],
» U is current link utilization, 0 to 1 [-],
» Q is link quality, 0 to 1 [-] or [%].

In WDM networks, evaluating of several wavelength channels must be done in each of link, so available capacity should be calculated for each wavelength channel. Thus, links capacity can be periodically obtained to get optimal routing topology in a dynamic changing utilization, quality and data transmission demands. In case of some emergency, traffic is flexibly rerouted using less faulty links to output node by proposed control system. In addition to the fastest path choice, alternative paths can be obtained.

Very important additional goal of proposed approach is to avoid optical-electrical-optical conversion as much as possible (due to significant data transfer delay) when switching is performed. Such conversion is usually performed when switching among different wavelength channels. Omitting optical-electrical-optical conversion thus routing via optical-optical conversion only may increase overall traffic throughput. [35]

Proposed complex optimization algorithm contains several steps to find the most appropriate path between chosen starting and destination nodes, among transport links involved in list. Control system processes input data in three steps. Firstly, OSNR, BER and Power triplet parameters are measured for each link or wavelength channel.

Subsequently, they are processed by fuzzy logic control subsystem and relationships are evaluated for each particular link or wavelength channel. Here, membership functions and fuzzy rules are defined by experienced user and trained by real training sets to obtain optimal links evaluation.

Finally, fuzzy logic system creates list of all link parameters between existing starting and destination nodes. As a result, final data transport path is selected from this list through selected nodes.

EXPERIMENTAL MODELLING AND SIMULATIONS

Measured OSNR, BER and Power parameter are continuously fed by each node into central fuzzy logic control subsystem. Its centralized diagnostic evaluates these parameters, calculates its probabilistic means during measuring interval.

Then, fuzzy logic processing sequentially executes typical processing steps: fuzzification, fuzzy decision making, and defuzzification.

Fuzzified input parameters at triangle shapes spread ranges:

» OSNR - numerical value spans from 10 to 1000 following linguistic expressions Very Low, Low, Middle, Acceptable and High,

» BER – numerical value spans from 10^{-12} to 10^{-8}; its linguistic expressions for this parameter are Very Low, Low, Acceptable, High and Very High,

» Power - numerical value spans from 0,001 W to 1 W; linguistic expressions for this parameter are Low, Acceptable, and High.

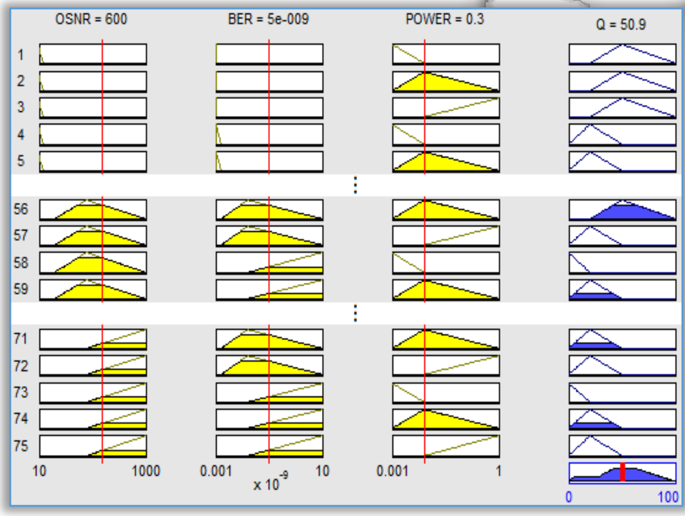

Figure 5. Triangle fuzzy rules setup view, among input and output parameters

The example of 75 fuzzy rules set is shown in Figure 5. Here, relationships among input triplet parameters and output Q parameter are defined to obtain output fuzzy values.

In the pictured example, for currently measured *OSNR* = 600, BER = 5e-9 and Power = 0.3, the output crisp parameter of *Q* = 50.9 represents overall quality and suitability of particular link or wavelength channel at Average level, of linguistic expression of Low, Substandard, Average and High level, spanning along interval <0,1> by triangle membership functions, Figure 6.

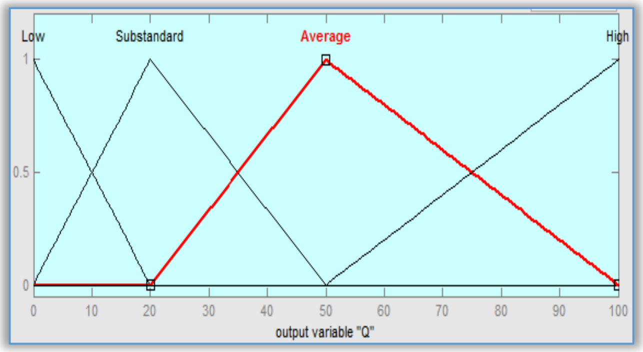

Figure 6. Triangle output Q fuzzy membership functions

PATHS EVALUATION AND ORDERING

After obtaining link costs i.e. available capacity $C_{available}$, all available paths located between chosen start and destination nodes are evaluated to define path reliability and stability. In proposed routing control subsystem, two calculation methods are implemented to assess all paths and to find the most appropriate one.

» **Maximum mean capacity of paths**

Capacity $C_{max,j}$ represents mean all-link value over each j-th available path (along n - number of links), Eq. 2. After paths ordering, the highest $C_{max,j}$ value is chosen to be the most appropriate path. As this method doesn't take into account the whole path balancing (i.e. the extreme link cost limits), another methods should be applied.

$$C_{max,j} = \left. \frac{\sum_{i=1}^{n} C_{available,i}}{n} \right|_{max,j} \tag{2}$$

» **Standard deviation setting of paths**

The second method uses another statistical parameter to weight each path. A standard deviation STD_j is composed over each *j*-th available path (along *n* - number of links). Then, the most appropriate path is selected by criteria of minimum deviation, Eq. 3. Unlike the previous method, this seems to be better justified since $STD_{min,j}$ parameter prefers a path with balanced links quality.

$$STD_{min,j} = \left. \frac{\sum_{i=1}^{n} STD_i}{n} \right|_{min,j} \tag{3}$$

» **Double-parameter setting of paths**

The third method rates previous statistical parameters for each path optimal weighing (maximum is applied), Eq. 4.

$$opt_{max,j} = \left. \frac{C_{max,j}}{STD_{min,j}} \right|_{max,j} \tag{4}$$

EXPERIMENTS AND DISCUSSIONS

In following experimental routing scenarios, above mentioned 17 GÉANT and 8 NRENs cross-border links are used. The parameters OSNR, BER, Power, U and C_{max} for each of them represent current links states. They are set either by sliders or typed via Graphical User Interface (GUI), see left area and top chart in Figure 7.

The merged network topology and nodes names are shown in the diagram placed in the middle in Figure 7 (high-speed GÉANT in green, low-speed GÉANT in dashed green, NRENs in orange). This model generates 132 total number of available routing paths. Above mentioned fuzzy control and statistical weighing algorithms are provided by Matlab and Simulink software.

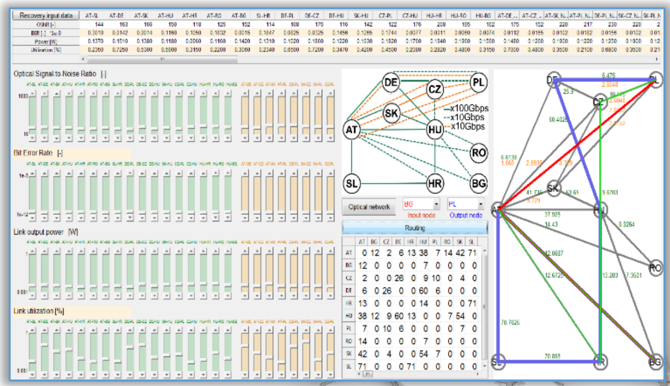

Figure 7. Simulation model and network topology

As a result of parameters settings and control mechanism calculations, available capacity $C_{available}$ is obtained for each of paths, see right-down chart and diagram in Figure 7. As a novel data transmission demand, the input BG and output PL nodes are chosen. Applying Equation 2, the blue line shows the path of maximum available capacity from starting node, via AT-SL-HR-HU-DE GÉANT links.

Here, the DE-PL link with the lowest cost along this path might delay overall throughput. Unlikely, following the Equation 3, the red line shows better balanced BG-AT-PL path for the same starting and destination nodes via two GÉANT and NRENs low-speed links only. Despite of lower links cost, this path is the shortest one and, it is better balanced than the blue one. Applying Equation 4, the green line represents the path of maximum available capacity with respect to path balancing via AT-HR-HU-CZ nodes. It represents low-speed GÉANT links, except for last CZ-PL NRENs link. To conclude achieved experimental results, the blue path is applicable for huge data bulks transmission in short period; the red one is more suitable for medium and small data bulks transmission; the green path fits to long-time data transfers.

CONCLUSIONS

Proposed middle-European plus neighboring merged network model comprehensively evaluates overall topology, comprising number of GÉANT and NRENs optical WDM links. To improve overall data transmission efficiency, reliability, stability and better utilization distribution over exploited links, the permanent link monitoring is necessary. When implementing algorithm in merged networks, more precise evaluation is needed for each link.

In standard routing algorithms, usually the only path is obtained to setup the most appropriate path for data transmission, by the decision algorithm in a control system. Moreover, standard routing algorithms provide simple assessment only. It might not be sufficient when network loading or utilization dynamically changes. In proposed solution, based on C_{max} capacity, each link is scored by fuzzy logic control subsystem, using several link parameters like OSNR, BER and Power. Consequently, link quality Q is obtained. Finally, routing control subsystem calculates overall links cost using current parameters like maximum available capacity and utilization. In this way, all available paths weighed quality is obtained. The most appropriate path can be chosen with respect to either maximum available capacity, minimum utilization fluctuations or maximum path balancing.

In case of an emergency situation, control system can recalculate link parameters and efficiently reroute existing links and thus recover into fully-operational state, excluding faulty links. This advantage designates it to be implemented quickly and seamlessly.

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[26] CESNET – an association of universities of the Czech Republic and the Czech Academy of Sciences - https://www.cesnet.cz
[27] PIONIER - Polish Optical Internet - a nationwide broadband optical network for e-science - http://www.pionier.net.pl/online/
[28] ACOnet - The Austrian Academic Computer Network (NREN) - http://www.aco.net/technologie.html?&L=1
[29] SANET – Slovak Academic Network - www.sanet.sk
[30] The National Information Infrastructure Development (NIIF) Program - http://www.niif.hu/
[31] Academic and Research Network of Slovenia: http://www.arnes.si/
[32] Croatian Academic and Research Network: http://www.carnet.hr/
[33] Romanian Education Network: www.nren.ro, http://webdevel.iasi.roedu.net/default.php?t=site&pgid=7
[34] Bulgarian Research and Educational Network: http://www.bren.bg/
[35] Gregory N. Nielson, Michael J. Shaw, Olga B. Spahn, Gregory R. Bogart, Michael R. Watts, Roy H. Olsson III, Paul Resnick, David Luck, Steven Brewer, Chris Tigges, Grant Grossetete: High-Speed, Sub-Pull-In Voltage MEMS Switching. SANDIA REPORT SAND2008-0211 Unlimited Release. Printed in January 2008.

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