SHORT-TERM SCIENTIFIC MISSION (STSM) FINAL REPORT

ON

ENERGY EFFICIENT AND RESILIENT OPTICAL NETWORKS

STSM Grantee - Matija Džanko, PhD
matija.dzanko@fer.hr

Home Institution - University of Zagreb, Faculty of Electrical Engineering and Computing, Department of Telecommunications
Zagreb, Croatia

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Host Institution - Professor Sofie Verbrugge
sofie.verbrugge@intec.ugent.be
Ghent University, Department of Information Technology
Ghent, Belgium

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1 INTRODUCTION

This report contains an overview of the short-term scientific mission (STSM) under COST Action CA15127 at Ghent University, Department of Information Technology, Ghent, Belgium, from 13th November to 20th November, 2016. The STSM underpins COST Action working group (WG 3 “technology-related disasters”).

2 DESCRIPTION OF WORK CARRIED OUT DURING STSM

The group from Ghent University is currently working on the development of network planning software, which will be reusable by other researchers. During the STSM, I worked on several parallel issues related to network planning and reliability, aiming at a more standardized approach allowing easy cooperation between different researchers. The issues considered (1) the development of a technical report for a resilient optical layer node, including an availability model for the proposed optical node, (2) preliminary study of network planning tools that could be extended with my availability model and (3) my contribution to the techno-economic portal currently being set-up at Ghent University that will be used to share most interesting tools, templates, reports and publications to the research community. Also, as a result of this STSM, I suggested two main issues that has to be resolved within WG3 of this COST Action, and are related to technology based disasters in optical networks. First one refers to evaluation of the vulnerability of communication networks to disaster-based disruptions, and the second one refers to the algorithms for resilient routing strategies. Therefore, I will contribute to the Action with the availability models of optical networks and nodes affected by technology-based distasters, and resilient routing for elastic optical networks based on network function programmable nodes.

The main topics that were my area of interest during my stay at Ghent University are as follows:

2.1 TECHNICAL REPORT FOR RESILIENT OPTICAL LAYER NODE

Technical report for resilient optical layer node was built in collaboration with Bram Naudts, PhD student. Main part of technical report, visualization of components within resilient optical node, is based on ECMN (Equipment Coupling Modelling Notation) [1]. ECMN is used to visualize the components of modular network equipment in an easy to understand, human readable format. This modelling notation was originally developed to calculate the cost of installation of the equipment in a central office. It exploits the hierarchical structure of a central office to determine the amount of equipment that needs to be installed and using graph structure visualizes how equipment is linked together. Clearly the same modelling notation can be used for dimensioning routers, servers, fibre links or any other equipment.

2.1.1 APPROACHES FOR INCREASING NETWORK RESILIENCY

In general, approaches for increasing network resiliency and reducing network vulnerability, along with the associated data and revenue losses, include *(i)* providing redundancy in the network that serves for failure recovery, and *(ii)* reducing the number of failure-prone components used by each lightpath, thus lowering the associated risk of failure. Failure recovery typically takes place at the network level by establishing one or more backup (redundant) lightpaths that are node and link disjoint with working lightpath. This redundant lightpath can be precomputed and reserved at connection setup time (protection), or upon a failure (restoration). Examples of approaches for network-level failure recovery with establishing of a backup lightpath can be found in [1] and [3]. Improvement of network availability via node-level recovery, i.e. self-healing inside nodes, as well as through reduction of the number of failure-prone components used by each lightpath, are novel functionalities enabled by network function programmable reconfigurable add-drop multiplexers (NFP ROADMs) based on Architecture on Demand (AoD) paradigm [4]. Cross-connections between optical components in AoD nodes, e.g., optical splitters, wavelength-selective switches (WSSs), (de)multiplexers or amplifiers, are realized in a highly flexible and reconfigurable manner via an optical backplane (e.g. high-port count 3-dimensional micro-electro-mechanical switch (3D MEMS) or piezoelectric optical switch (POS)), thus providing the network with an unparalleled adaptability to traffic diversity and variations. Deployment of AoD nodes has been shown to be particularly beneficial for improving network availability and energy efficiency [5] and [6].

2.1.2 OPTICAL NODE MODEL

Our resilient optical node was implemented using AoD paradigm. An AoD node comprises a number of inputs and outputs, and a set of modules connected to an optical backplane implemented by a large port-count optical switch. Building modules can be either single devices for optical processing such as multiplexer (MUX), demultiplexer (DEMUX), bandwidth variable wavelength selective switch (BV-WSS), spectrum selective switch (SSS), or subsystems composed of several devices. The aim of AoD is to address the limitations of existing optical cross-connects (OXCs) and reconfigurable optical add-drop multiplexers (ROADMs) by providing flexible processing and switching of optical signals through customised/programmable architectures per degree according to traffic requirements. Unlike existing optical node architectures, in AoD the components used for optical processing are not hard-wired within the architecture but can be interconnected together in a completely arbitrary manner. They can be dynamically added/removed from implemented optical node architectures or relocated anywhere within an architecture to form new arrangements. Figure 1 illustrates an example scenario of AoD where a number of architecture-building modules are attached to an optical backplane implemented by a large port-count 3D-MEMS optical switch. Optical node architectures are constructed by interconnecting suitable architecture-building modules using cross-connections in the optical backplane. Architectures that support the processing and switching requirements of arbitrary input signals are computed and implemented. This process can be performed by a user-driven or automated mechanism. As architectures utilise only the architecture-building modules needed to provide the required functionality, the requested switching complexity is reflected on the complexity of the implemented architecture. For instance, in the example architecture depicted in Figure 1 only one cross-connection is used to switch traffic from input #1 to output #1 (fibre switching). Conversely, traffic going from input #2 to output #N has a more complex switching requirement that is realised by a splitter and a BV-WSS. Thus, each AoD port may potentially implement different levels of switching granularity, from fibre switching to sub-wavelength switching.

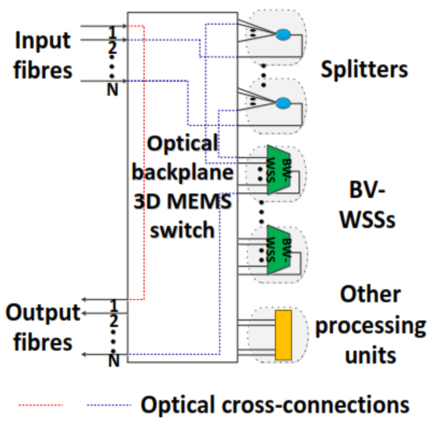

Figure 1. AoD node model

In order to model AoD node in a sense that we are able to calculate the cost in the process of node dimensioning, we have built an ECMN model of AoD node. The model is shown in Figure 2.

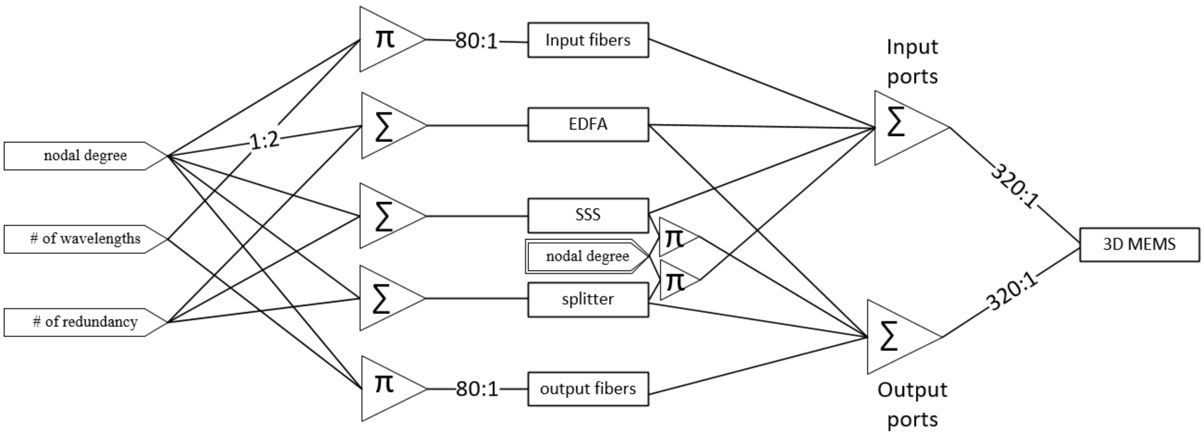

Figure 2. ECMN model for AoD node

The number of components within AoD node will be determined based on nodal degree, number of wavelengths, and number of added redundant components (this number can be 0, if there is no desire for assigning additional redundant components within the node). The number of input and output fibres is determined based on the product of nodal degree and number of wavelengths, while the number of components (EDFAs, SSSs and splitters) is calculated as a sum function of nodal degree and number of added redundancy. We assume that 80 wavelengths per fibre are deployed. The assumed size of 3D MEMS switch is 320 × 320. If used components occupy more than 320 input or output ports, additional 3D MEMS is required. This condition is checked by summing the number of ports used by the components.

After finishing the model, we need to define prizes for each component within the node. The prizes are expressed in relative cost, while the unit price (in this case relative cost is 1) is $3,500. The component relative cost was collected come from personal communication with vendors and researchers in the area. Table 1 summarizes the prices of used component within the ECMN node model, and are found in [8].

Table 1. Component prices for ECMN model

Component	Symbol	Relative cost
320 x 320 MEMS switch	MEMS OXC	23
8 x 8 MEMS connections	CON	5
Spectrum selective switch 1:*N*	SSS	7.5 + 0.5 x *N*
Splitter	SPL	0.015

Also, in order to evaluate availability and power consumption of an AoD node, it is important to add failure rates, insertion loss and power consumption of used components. These data are given in Table 2, together with associated references.

Table 2. Failure rates, insertion loss and power consumption of AoD components

Component	Failure rate in FIT	Insertion loss in dB	Power consumption in W
SSS	2000 [9]	6 [13]	40 [6]
Splitter 1:N	25 · N [10]	10 log *N*	-
MEMS mirror	21 [11]	3 [14]	45 [13]
EDFA	2000 [12]	-	15 [6]

2.2 AVAILABILITY MODEL FOR RESILIENT OPTICAL LAYER NODE

For AoD node, we have defined procedure for evaluating availability, that will be used in future collaboration for availability calculation of different node architectures within the COST project.

Generally, the availability A(t) of a component is defined as the probability that a component works correctly at the moment of observation *t*. Steady-state availability (hereinafter availability) of a component can be calculated from its failure and repair rates. Under constant component failure rate λ and repair rate μ, the time to failure TTF and time to repair TTR of a component, which has an exponential distribution, are calculated as follows:

$$\mathrm{TTF} = -\ln\frac{(1-x)}{\lambda}, \quad (1)$$

$$\mathrm{TTR} = -\ln\frac{(1-x)}{\mu}, \quad (2)$$

Where x is random number, x ε (0,1].

For each component within the node (or within the network, when this availability model is extended on the network level) we can define a failure rate, which we assume to be constant over time. The failure rate λ is often measured in units of "failure in time (FIT)". The failure rate is a standard unit used for specifying failure rates, or conversely mean time to failure (MTTF), and it is defined as number of failures in 10^9 hours. FIT is defined by equipment vendors for each optical component or module. The MTTF of a network component is the average time that a component is operational before a failure occurs, and it is inverse value of the failure rate λ.

$$MTTF = \frac{1}{\lambda}, \tag{3}$$

For repairable systems, it is necessary to define repair rate μ. For all components, we assume that the time to repair is also exponentially distributed. We also define the mean time to repair (MTTR), which is equal to

$$MTTR = \frac{1}{\mu}, \tag{4}$$

MTTR is the average time that it takes to repair a failed component. In most cases, MTTR includes a short time to detect failure occurrence. Further on, MTTR includes time to diagnose fault and its location. Finally, MTTR includes some time to perform the appropriate action to fix the link/component, and return it into proper working state. In an ideal situation, the time to detect, diagnose and repair a network problem will be measured in minutes. However, sometimes failures happen over the night or in dislocated areas and then the whole procedure is measured in hours. The mean time between failures (MTBF) of a repairable component is the average time between two consecutive failures, and is equal to sum of the MTTF and MTTR. Because the MTTR is typically small compared to the MTTF (MTTR « MTTF), the MTBF is almost equal to the MTTF.

$$MTBF = MTTF + MTTR \approx MTTF. \tag{5}$$

Availability A is calculated per the following:

$$A = \frac{\mu}{\lambda+\mu} = \frac{MTTF}{MTTF+MTTR}. \tag{6}$$

Unavailability U, which is complement of A, is used more frequently as a more suitable measure:

$$U = 1 - A. \tag{7}$$

To assess availability performance of the internal structure of an AoD node presented with ECMN model, we model the 3D-MEMS optical backplane as two sets of mirror arrays, where each mirror has a failure rate obtained from the literature, with value as in Table 2. Employing an optical backplane with unused ports allows us to model the reparation process of mirrors as an action in which the fibre or the component associated to the port with the failed mirror is manually relocated to another port whose corresponding mirror is in fully operational, working state. Thus, a failure of an individual mirror does not necessarily imply that the optical backplane must be replaced, as long as there are enough ports with working mirrors. Replacement of the whole backplane typically takes place within scheduled maintenance during which lightpaths are handled by spare network resources with a negligible impact on their down time.

In order to calculate exact availability values for a given node design, analytical calculation or Monte Carlo simulation has to be conducted. Monte Carlo simulation is based on an idea to use random samples of parameters or inputs to explore the behaviour of a complex system or process, where generated values of a random variable are based on one or more probability distributions. Monte Carlo method was used broadly to analyse network reliability and availability in recent years [15-19]. Analytical calculation is based on the expression 3-7, while our proposed Monte Carlo simulation, for simulation of failures and repairs of node components, is performed using following steps:

1. In time zero, all components are set to failure-free state.
2. Exponentially distributed time to failure (TTF) and time to repair (TTR), for each component in the node architecture, are calculated according to the expression (1) and (2).
3. Each lightpath is affected by the failures of the traversed components. The failures and reparations of component create distinct lightpaths timelines, alternating between ON and OFF states. For each lightpath, the cumulative ONtime and OFFtime are recorded.

$$A = \frac{ONtime}{ONtime + OFFtime}, \tag{8}$$

4. Based on the availability of all lightpaths passing through the node, different node availability measures can be represented: A_{st} availability, A_{av} and A_{100} availability. A_{st} represents minimal availability within all set of lightpaths, while A_{av} denotes the

average availability of all lightpaths. A_{100} availability is defined as a probability that all lightpaths are in faulty-free state.

Using the above described simulation settings and procedure, we are possible to study different node configurations with different traffic demands. Moreover, this simulation procedure can be used on the network level, when evaluating availability of large scale (optical) networks.

2.3 AVAILABILITY SIMULATION MODEL INCLUDED IN TRS LIBRARY

Within this week spent at imec, I was thoroughly acquainted with the software that is used at the group of Prof. Verbrugge. A part of the research is based on the following tools: BEMES (Business modelling and simulation tool) and TRS (Telecom Research Software). BEMES uses ECMN as a standardized language for modelling the costs of investments in equipment, while TRS is generic graph library that enables development of different routing algorithms on any multi-layer networks, while also supporting execution of event-based simulation. TRS is based on Grph, Java graph toolkit enabling experimentation of large graphs (in the order of millions of nodes). Grph proposes a general graph model taking into an account computational and memory efficiency and usage simplicity. In cooperation with Jonathan Spruytte, my goal is to add my fault simulation procedure into TRS software, in order to create tool that will be able to determine vulnerability of different kinds of networks. This goal is not feasible in short term, but it will be developed during this COST project.

2.4 TECHNO-ECONOMIC PORTAL

During the STSM I discussed with Marlies Van der Wee and Sofie Verbrugge my potential contribution to the techno-economic research portal that is currently being set up by Ghent University. The techno-economic research portal will unite relevant research groups to collect generic methodologies, useful tools, frameworks and international literature that will be made available to the scientific community. The portal is not online yet, but the researchers at Ghent University are doing the final steps to put a first version online by the end of this year. I will participate in the creation of content related to the following topics:

1. Telecommunication network resilience (how to make network less vulnerable, with explaining different metrics for evaluating network vulnerability)
2. Design of multi-granular and elastic optical nodes
3. Optical switching technologies

4. Event-based simulations for availability calculations

Also, my research group at University of Zagreb will be part of the portal, hence providing input on relevant events, news, and existing publications that will be potentially interesting to other researchers.

3 FUTURE COLLABORATION WITH HOST INSTITUTION (IF APPLICABLE)

Based on the aforementioned contributions, future collaboration with the group from Ghent University can be structured according to the timing as follows:

- Short term collaboration (next few months):
  - Release of the technical report of the optical layer node
  - Improvement of the techno-economical portal
- Medium term collaboration (within one year):
  - Extended version of the technical report, with different use cases, published as a journal paper
- Long term collaboration (more than one year):
  - Extension of the TRS library with the availability and fault simulation model
  - Work on the other topics that will arise within this COST project

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