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Scientific Report: Short Term Scientific Mission in COST Action CA5127 RECODIS

1. STSM details

STSM title: Protection in SDM networks

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2. Purpose of the STSM:

Spatial division multiplexing (SDM) is a new proposal for efficient support of ever increasing traffic in transport optical networks. The technology brings the possibility to extend the capacity limit of a typical physical link by joint transmission using a number of spatial resources (i.e., fiber cores or modes) [1], [2].

Besides the extended available bandwidth, the simultaneous transmission over a number of spatial resources also brings forth the problem of crosstalk between adjacent spatial resources that transmit signals at the same frequency [3]. The crosstalk level depends on a number of various parameters wherein the most important are transmission distance, characteristics of a fiber bundle and the number of neighboring spatial resources. It is worth-mentioning that for the multi-core fibers, the worst case scenario affects a central core that has the highest number of neighboring resources. Each modulation format, which can be used for data transmission in SDM network, has a specific tolerance to crosstalk [3], [4]. When the crosstalk level is too high, the transmitted signal cannot be correctly detected at the destination node. As a consequence, crosstalk can reduce transmission distance of the applied modulation formats [3].

There are several SDM realization possibilities depending on the applied transponders and fiber types: (*i*) independent switching, (*ii*) fractional switching, (*iii*) joint switching [5]. The independent switching policy brings the possibility to use spectral channels that can group a number of frequency slices, however, they use only one spatial resource. Then, the fractional switching policy allows to use spectral-spatial channels that use a number of frequency slices and, at the same time, a number of spatial resources (a subset of all available resources). Eventually, the joint switching policy also brings spectral-spatial channels, however, it has all available spatial resources at disposal. According to the literature, the independent policy is the most spectrally-efficient SDM realization [6].

The SDM networks bring new advantages as well as new challenges. They are also prone to failures and attacks. Since the technology is rather new, its survivability has not extensively studied in the literature. Therefore, the aim of the STSM visit was to start collaboration focused on the analysis of the SDM network vulnerabilities, possible failure/attack scenarios and some survivability mechanisms.

3. Description of the work carried out during the STSM and the main results obtained

During the STSM, the Applicant and the Host have analyzed the SDM network vulnerabilities, possible failure/attack scenarios and some survivability mechanisms. Based on the discussion, the participants decided to focus on two research questions.

<u>Research question 1: Disruptive signal jamming in SDM networks</u>

The SDM technology suffers from crosstalk between adjacent spatial resources. Moreover, the SDM-based networks are also prone to disruptive signal jamming. The coexistence of two disruptive phenomena (i.e., crosstalk and injection) can significantly reduce the transmission distance for legitimate signals carrying user data. Therefore, the aim of the study is to evaluate how different signal jamming scenarios can influence the transmission distances in SDM-based networks (considering crosstalk) and how to protect the network against the most harmful signal injections.

The research findings are planned to be submitted for the OFC 2018 conference.

<u>Research question 2: Spectrum and attack-aware restoration in SDM networks</u>

The possibility to allocate spectral channel on different spatial resources (independent switching) and the possibility to reduce channel width in the frequency domain by joint transmission on a number of spatial resources (fractional switching) are expected to provide efficient flow restoration in SDM networks. The second research question concerns spectrum and attack aware dimensioning and flow restoration in flex-grid SDM network. The problem can be divided into two phases: network dimensioning and flow restoration after a single link failure (caused by an attack).

Phase 1: Spectrum- and attack-aware network design

The first part of the consideration is spectrum and attack aware network planning. The aim is to minimize maximum spectrum usage and network vulnerability to link attacks. The considered spectrum usage is defined as the total amount of spectrum slots required in the network to support a given set of traffic demands. To obtain network vulnerability to link attacks, for each network link we define a *link risk parameter* that is proportional to the probability of an attack on that physical link. In more details, the higher link risk parameter, the more likely that the link will be attacked. The link risk parameters are obtained based on the analysis of the links importance for the overall network connectivity. Then, for each routing path selected for a demand we sum the value of risk parameters of the included links. The overall *network vulnerability to link attacks* is a sum of risks obtained for the selected paths for all demands.

The network planning phase is performed in two steps. In the first step, we solve optimally (using integer linear programming, ILP, model) network planning problem with respect to the spectrum usage. The aim of that problem is to find replica placement and routing rules (light-paths for demands in SDM flex-grid network) in order to minimize the maximum (i.e., total) spectrum usage. The problem solved in the first step can be defined as follows:

NETWORK PLANNING WITH RESPECT TO MAXIMUM SPECTRUM USAGE

Given:

- Network topology
- Traffic demands (one-directional anycast demands)
- Number of replicas in the network
- Candidate nodes to host replicas

To find:

- Routing rules
- Locations of replicas

Objective (to be minimized):

- Maximum spectrum usage – *MaxSpec*

Then, in the second step we try to improve obtained solution in terms of the network vulnerability to link attacks. To this end, we solve optimally (using ILP model) network planning problem with respect to the network vulnerability to link attacks wherein the maximum spectrum usage obtained in the first step is used a spectrum usage constraint. In more details, we assume that spectrum usage cannot be higher than the obtained value and α% margin (i.e., (1+α) x *MaxSpec*). The aim of that problem is to find replicas placement and routing rules (light-paths for demands in SDM flex-grid network) in order to minimize network vulnerability to link attacks. The problem solved in the second step can be defined as follows:

NETWORK PLANNING WITH RESPECT TO THE NETWORK VULNERABILITY TO LINK ATTACKS

Given:

- Network topology
- Traffic demands (one-directional anycast demands)
- Number of replicas in the network
- Candidate nodes to host replicas
- Link risk parameters
- Maximum spectrum usage in the network (value obtained in the previous step + α% margin)

To find:

- Routing rules
- Locations of replicas

Objective (to be minimized):

- Network vulnerability to link attacks

Phase 2: Spectrum and attack-aware flow restoration

With a given optimized network (with respect to spectrum and vulnerability to link attacks), the link attacks are simulated. The attacked link is selected randomly with respect to link risk probabilities. After a link attack, the heuristic procedure tries to restore network connectivity and minimize rejected bitrate. Additionally, as the secondary optimization criteria, the restoration process tries to provide low network vulnerability to link attacks. The flow restoration problem can be defined as follows:

FLOW RESTORATION

Given:

- Network topology (with limited spectrum resources)
- Replicas locations
- Link risk parameters
- Traffic demands (one-directional anycast demands) with assigned routing rules
- Attacked link

To find:

- Routing rules
- Locations of replicas

Objective (to be minimized):

- Rejected bitrate
- Network vulnerability to link attacks

The research findings are planned to be submitted to Journal of Lightwave Technology or Journal of Optical Communications and Networking.

4. Future collaboration with the Host institution

The STSM applicant and the Host are planning to continue collaboration concerning resilient networks. The plans for future works include, among others, extensions of the previously discussed restoration in SDM networks by focusing on dynamic traffic scenarios.

5. Foreseen publications/articles resulting from the STSM

Currently, the STSM applicant and Host are planning to prepare two publications – one regarding disruptive signal jamming in the SDM networks (planned to be submitted for OFC 2018), the second one regarding flow restoration in SDM networks (planned to be submitted to Journal of Lightwave Technology or Journal of Optical Communications and Networking).

6. References

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[4] A. Muhammad, G. Zervas, D. Simeonidou, R. Forchheimer, "Routing, spectrum and core allocation in flexgrid SDM networks with multi-core fibers", ONDM 2014.

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[6] P. Lechowicz, K. Walkowiak, M. Klinkowski, "Spectrum usage for various SDM scenarios", ICTON 2017.