Physical topology abstraction for SDM optical networks

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Abstract—The new technologies in the field of optical networking allow to augment the capacity of the optical channel taking advantage of the spatial multiplexing. Parallel fibers, multi-core, or multi-mode fibers enable space-division multiplexing (SDM). Multi-core and multi-mode fibers introduce additional physical impairments that should be considered when provisioning a lightpath.

In Software Defined Networks (SDN), the centralized controller holds the overall view of the network including physical layer information required to estimate quality of transmission (QoT). SDN controllers may rely on the so called *impairment-aware topology* to perform lightpath provisioning while guaranteeing QoT. Such topology abstraction associates physical parameters to network links/paths. Recently, given the great interest on the NETCONF protocol, impairment-aware topologies have been described through the YANG data modelling language. Such topology model is dependent on the network technology.

In this paper, we present a YANG model for impairment-aware physical topology in SDM optical networks. This model can be used by a network controller to compute and set up a connection by using the path with the lowest impairments. An experiment shows an ONOS controller exploiting the impairment-aware topology for connection setup in SDM networks affected by cross-talk and mode-dependent loss.

Index Terms—SDM, Optical Networks, SDN, YANG/NETCONF

I. INTRODUCTION

SDM transmission is under investigation as a way to increase the capacity of optical networks exploiting the spatial dimension in addition to the spectrum [1]. SDM leverages parallel standard fibers or multi-core and multi-mode fibers, where multiplexing is implemented in different fibers, cores, or modes, respectively. Several studies are investigating the enabling technologies including demultiplexing [2] and amplification [3]. Other studies are focused on the physical characterization of multi-core and multi-mode fibers modelling degrading effects such as cross-talk [4] and mode-dependent loss (MDL) [5], [6].

These models can be exploited during network design, by the network management system, or by a Software Defined Network (SDN) controller for *routing, spectrum, and spatial dimension assignment*, in order to identify a route, a set of cores (or modes and fibers), and a portion of spectrum to accommodate a given connection request [7]–[9]. Moreover, network protocols and data models should be refined to account for specific transponder parameters to be configured, i.e., for correctly detecting a signal in multi-core or multi-mode optical networks (e.g., considering core or mode cross-talk). As an example, the authors of [10] proposed a YANG model [11] for the NETCONF protocol [12] in order to properly configure and monitor multidimensional (spectral and spatial) transceivers. However, investigations on YANG and NETCONF are still needed in this field. An example is the abstraction of an impairment-aware topology [13]. Indeed, currently, a group within the Internet Engineering Task Force (IETF) is developing a YANG model for the impairment-aware topology in elastic optical networks. The intent of the IETF document is to provide a YANG data model, which can be utilized to collect states of network impairment data to enable an SDN controller for impairment-aware optical path computation. Until now, SDM has not been investigated in terms of YANG data modeling for impairment-aware topology.

In this paper, we present a YANG data model to describe impairment-aware physical topology in SDM optical networks based on multi-core or multi-mode fibers. Such data is then used by an SDN controller to set up a connection accounting for the physical impairments typically affecting multi-core and multi-mode fibers. The topology abstraction accounts for the interactions between spatial modes (including also cores in this terminology), depending on the operation regime of the SDM network. An experimental demonstration is shown through a control plane testbed where an ONOS controller [14] leverages, for connection setup, an XML-based impairment-aware topology database built on the proposed YANG model.

II. IMPAIRMENT-AWARE TOPOLOGY FOR SDM NETWORKS

Impairment-aware topology abstraction in SDM networks has to account for physical-layer impairments raising in SDM fibers. Besides optical signal to noise (OSNR) degradation due

```
+--ro OMS-attributes
   +--ro generalized-snr?        decimal64
   +--ro (power-param)?
   +--ro media-channel-group* [i]
      +--ro i                     int16
      +--ro media-channels* [flexi-n]
         +--ro flexi-n            uint16
         +--ro flexi-m?           uint16
         +--ro type_fiber
         +--ro (type_fiber)
            +--:(SMF)
               +--ro fiber*       string
            +--:(MMF)
               +--ro mode*        string
            +--:(MCF)
               +--ro core*        string
   +--ro OMS-elements* [elt-index]
      +--ro elt-index   uint16
      +--ro type        identityref
      +--ro element
         +--ro i?                -> ../../../media-channel-
group/i
      +--ro (element)?
         +--:(amplifier)
            +--ro amplifier
               +--ro type_variety    string
               +--ro operational
                  +--ro actual-gain     decimal64
                  +--ro noise-figure    decimal64
                  +--ro out-voa         decimal64
                  +--ro in-voa          decimal64
                  +--ro power-param     decimal64
         +--:(fiber)
            +--ro fiber
               +--ro (type_variety)
                  +--:(SMF)
                  +--:(MMF)
                     +--ro modelist*              string
                     +--ro coupled-mode-list
                        +--ro mode-id-list* [id]
                           +--ro id              uint32
                           +--ro mode-id*        string
                           +--ro coupling-MMF?   decimal64
                     +--ro MDL?                   decimal64
                  +--:(MCF)
                     +--ro corelist*              string
                     +--ro coupled-core-list
                        +--ro core-id-list* [id]
                           +--ro id              uint32
                           +--ro core-id*        string
                           +--ro coupling-MCF?   decimal64
                     +--ro XTalk?                 decimal64
               +--ro length                 decimal64
               +--ro loss_coef              decimal64
```

Annotations: optical connections; amplifier attributes; MMF attributes — List of modes with a given coupling; MCF attributes — List of cores with a given coupling.

```
   +--ro pmd?                        decimal64
augment /nw:networks/nw:network/nw:node/tet:te/tet:tunnel-
termination-point:
   +--ro transponders-list* [transponder-id]
      +--ro transponder-id             uint32
      +--ro (mode)?
         +--:(explicit_mode)
            +--ro mimo-on?                  boolean
            +--ro mimo-modes
               +--ro mode-list* [id]
                  +--ro id        uint32
                  +--ro mode-id*  string
            +--ro mimo-cores
               +--ro core-list* [id]
                  +--ro id        uint32
                  +--ro core-id*  string
            +--ro bandwidth* [id]
               +--ro id          -> ../../mimo-modes/mode-list/id
               +--ro bandwidth?  decimal64
      +--ro available-modulation-types*   identityref
      +--ro configured-modulation-type?   identityref
      +--ro available-baud-rates*         uint32
      +--ro configured-baud-rate?         uint32
      +--ro available-FEC-types*          identityref
      +--ro configured-FEC-type?          identityref
      +--ro FEC-code-rate?                decimal64
      +--ro FEC-threshold?                decimal64
      +--ro pol-multipl-on?               boolean
   +--ro power?                           int32
augment /nw:networks/nw:network/nw:node/tet:te/tet:tunnel-
termination-point:
   +--ro transponder-list* [carrier-id]
      +--ro carrier-id    uint32
```

Annotation: List of modes/cores simultaneously detected by a MIMO receiver on a given bandwidth.
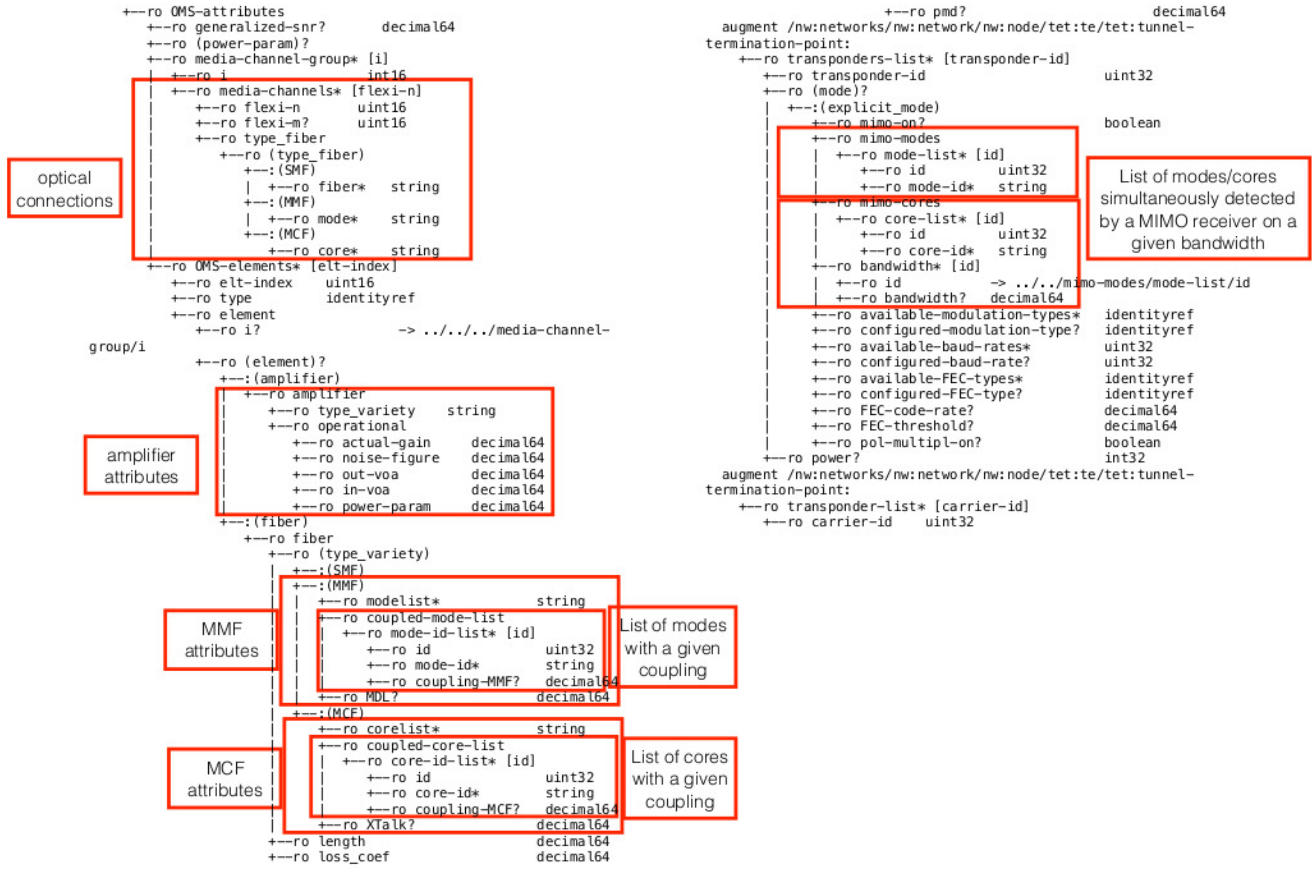
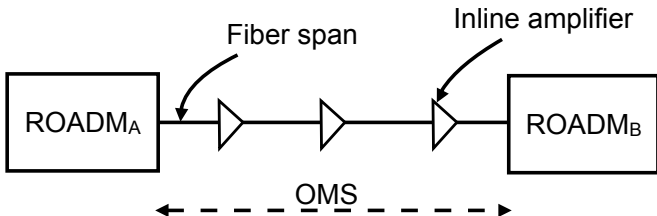Fig. 1: YANG data model for impairment-aware topology in SDM networks

Fig. 2: Optical Multiplex Section components

to amplified spontaneous emission and non-linear impairments such as self- and cross-phase modulation, typically accounted in networks based on standard fibers, other effects should be considered, depending on the SDM transmission implementation. Here we consider two relevant regimes of operation. In the first one, the spatial modes are ideally uncoupled, as is the case of multi-core fibers (MCFs) with nominally uncoupled cores, where the individual cores can be considered as single-mode fibers. In this case, dynamic inter-core cross-talk [4] arising from deployment-related issues and environmental perturbations is the additional impairment to be accounted for in the SDM network abstraction. In the second regime of operation, all spatial modes are strongly mixed with each-other as in the case of coupled-core MCFs. Thus, the extraction of the transmitted data relies on multiple-input-multiple-output (MIMO) processing, and MDL is a major impairment to be considered. MDL is a non-unitary effect responsible for a fundamental system capacity loss [5]. MDL fluctuations beyond some tolerable threshold must be considered in the topology abstraction.

YANG [11] is a data modelling language typically used to describe configuration (e.g., the modulation format of a transponder) and state parameters (e.g., state parameters are used to report the *state* value of a given parameter, such as the ones monitored for operation administration and maintenance purposes). In this paper, we consider YANG to model the physical-impairment topology of an SDM network, as done in [13] for networks operating with single mode fibers. Fig. 1 shows the tree of the proposed YANG model for impairment-aware topology in SDM networks. As done in [13], the tree is composed of two main branches: *i)* the Optical Multiplex Section (OMS) link representing the optical link connecting two reconfigurable add and drop multiplexers (ROADMs); *ii)* the termination points (transponders). OMS carries a set of media channels, which represent the optical connections described by the ITU-T n and m parameters and by a list of parallel fibers, or cores, or modes. OMS is then composed of a set of elements (identified by `elt-index`): amplifiers and
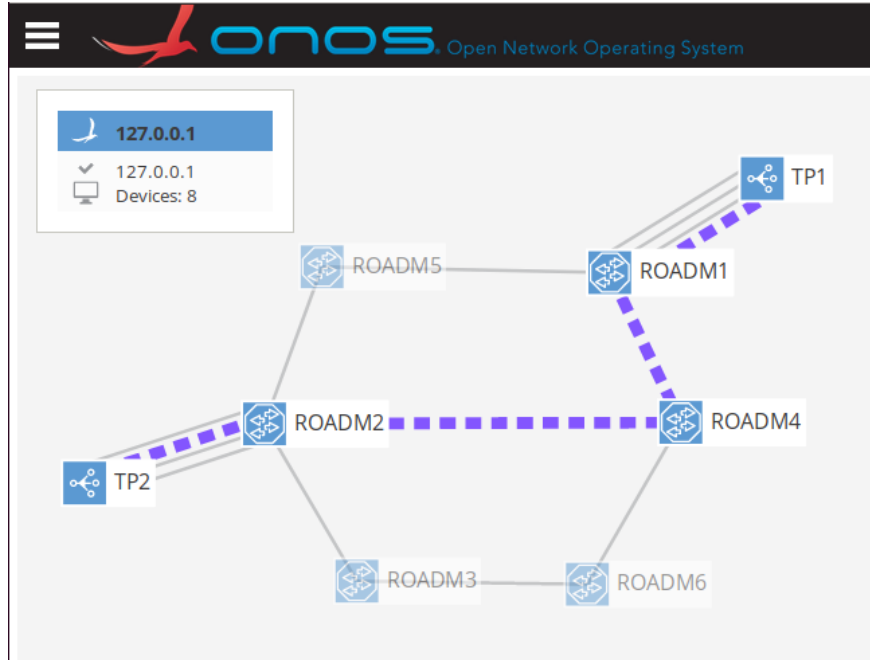
Fig. 3: Network topology

fibers (Fig. 2). The formers are characterized by a type (inline, booster, or pre) and by operational attributes including gain, output power, and noise figure. Fibers can be standard (single mode fibers - SMF), MCFs or multi mode fibers (MMFs). MMFs present a list of modes while MCFs a list of cores, while SMFs have no extra attributes. Coupling between modes or cores is defined by the parameters `coupled-mode-list` and `coupled-core-list`, respectively. Each one is composed of a list of modes (or cores) and their coupling value in dB. `XTalk` and `MDL` are the average cross-talk values from each neighbor core and the average MDL, respectively. Finally, other fiber parameters are associated to the length, loss, and dispersion.

Then, the termination point branch is composed of a list of transponders for both transmitter and receiver ends. In particular, regarding the receiver, the boolean parameter `mimo-on` identifies the adoption of MIMO detection or not. If MIMO is exploited, the receiver simultaneously processes a list of cores or modes (`mimo-cores` or `mimo-modes`, respectively) on a given `bandwidth`. Then, other transmission parameters are specified identifying transmission parameters such as the symbol rate and forward error correction (FEC).

III. EXPERIMENTAL DEMONSTRATION

An ONOS controller is used in a control plane testbed considering the network topology in Fig. 3. A connection request is assumed between transponders TP1 and TP2. ONOS evaluates two possible routes: path1 (ROADM1-ROADM5-ROADM2) and path2 (ROADM1-ROADM4-ROADM2). The choice of the route is performed exploiting the proposed impairment-aware topology. In particular, according to the YANG data model described in the previous section, ONOS

leverages an impairment-aware topology database encoded in XML.

The two regimes of operation, *strong* and *weak coupling*, have been both considered and some details of the related physical-impairment-aware topologies are shown in Figs. 4 and 5, which present physical information of the two paths assuming that cross-talk and mean square MDL linearly accumulate along spans. The cross-talk per unit spec is available in fiber specifications. MDL can be monitored through the channel transfer matrix across the signal spectrum, which is necessary for MIMO processing. Notice that MDL results from various loss sources (including primarily fiber splices and other deployment-related issues) but also from inline amplification [15]. More specifically, Fig. 4 shows path1 (Fig. 4(a)) and path2 (Fig. 4(b)) in a network with weak coupling exploiting uncoupled-core four-core fibers, while Fig. 5 shows the same paths in a network with strong coupling. As an example, the highlighted attributes of Fig. 4(a) show the coupling between the four cores with weak coupling: we assumed that pairs of neighbor cores $\{m_1, m_2\}$, $\{m_2, m_3\}$, $\{m_3, m_4\}$, and $\{m_4, m_1\}$ present a relatively large coupling of -25dB after 160 km; the coupling is reduced between non-neighbor cores $\{m_1, m_3\}$ and $\{m_2, m_4\}$ (-50dB after 160 km). On the other hand, the same attributes — associated to the other network scenario — in Figs. 5(a) and 5(b) present a coupling of 0dB, corresponding to a strong coupling between spatial modes. Considering the aforementioned connection request and the impairment-aware database, the SDN controller selects a path according to the the following quality of transmission model. In the case of uncoupled-core fibers, we consider a required OSNR level of 21 dB at a symbol rate of 24 GBaud and we assume average cross-talk values from each neighbor core of

Path1 - Weak coupling

```xml
<fiber>
    <MCF>
        <corelist>c1</corelist>
         <corelist>c2</corelist>
        <corelist>c3</corelist>

        <coupled-core-list>
            <core-id-list>
                <id>1</id>
                <core-id>c1</core-id>
                <core-id>c2</core-id>
                  <coupling-MCF>-25</coupling-MCF>
             </core-id-list>
            <core-id-list>
                <id>2</id>
                <core-id>c2</core-id>
                <core-id>c3</core-id>
                  <coupling-MCF>-25</coupling-MCF>
            </core-id-list>
            <core-id-list>
                <id>3</id>
                <core-id>c3</core-id>
                <core-id>c4</core-id>
                  <coupling-MCF>-25</coupling-MCF>
            </core-id-list>
            <core-id-list>
                <id>4</id>
                <core-id>c4</core-id>
                <core-id>c1</core-id>
                  <coupling-MCF>-25</coupling-MCF>
            </core-id-list>
            <core-id-list>
                <id>5</id>
                <core-id>c1</core-id>
                <core-id>c3</core-id>
                  <coupling-MCF>-50</coupling-MCF>
            </core-id-list>
            <core-id-list>
                <id>6</id>
                <core-id>c2</core-id>
                <core-id>c4</core-id>
                  <coupling-MCF>-50</coupling-MCF>
            </core-id-list>
        </coupled-core-list>
<XTalk>-24.0</XTalk>
```

(a) Path 1

Path2 - Weak coupling

```xml
<fiber>
    <MCF>
        <corelist>c1</corelist>
         <corelist>c2</corelist>
        <corelist>c3</corelist>

        <coupled-core-list>
            <core-id-list>
                <id>1</id>
                <core-id>c1</core-id>
                <core-id>c2</core-id>
                  <coupling-MCF>-25</coupling-MCF>
             </core-id-list>
            <core-id-list>
                <id>2</id>
                <core-id>c2</core-id>
                <core-id>c3</core-id>
                  <coupling-MCF>-25</coupling-MCF>
            </core-id-list>
            <core-id-list>
                <id>3</id>
                <core-id>c3</core-id>
                <core-id>c4</core-id>
                  <coupling-MCF>-25</coupling-MCF>
            </core-id-list>
            <core-id-list>
                <id>4</id>
                <core-id>c4</core-id>
                <core-id>c1</core-id>
                  <coupling-MCF>-25</coupling-MCF>
            </core-id-list>
            <core-id-list>
                <id>5</id>
                <core-id>c1</core-id>
                <core-id>c3</core-id>
                  <coupling-MCF>-50</coupling-MCF>
            </core-id-list>
            <core-id-list>
                <id>6</id>
                <core-id>c2</core-id>
                <core-id>c4</core-id>
                  <coupling-MCF>-50</coupling-MCF>
            </core-id-list>
        </coupled-core-list>
<XTalk>-21.0</XTalk>
```

(b) Path2

Fig. 4: Details of the impairment-aware topology database in the weak coupling scenario for two different paths

-24 dB in one path and -21 dB in the other, with the result that the first path is selected. In the second case of fibers with strongly coupled cores, we assume average MDL values of 12 and 8 dB in the two paths. As can be seen in Fig. 6, where we plot the capacity loss per mode versus the average link MDL in a fiber with N strongly coupled cores (and, more in general, for a fiber with N strongly mixed spatial modes), this corresponds to about 0.38 and 0.17 bits/s/Hz capacity loss per mode, respectively [6]. In this case the second path is selected because of the lower capacity loss. A similar graph is not reported for the case of weak coupling given that, in such a scenario, cross-talk can be simply considered as an OSNR penalty. Path computations are completed in few milliseconds.

IV. CONCLUSIONS

In this paper, we introduced a YANG model to represent physical-impairment-aware topology in SDM optical networks. This model is exploited by an SDN controller for path computation and connection set up. Experimental demonstration has shown its use case in two different network scenarios, considering both strong or weak coupling between spatial modes.

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Path1 - Strong coupling

```
<coupled-mode-list>
    <mode-id-list>
        <id>1</id>
        <mode-id>m2</mode-id>
        <mode-id>m3</mode-id>
        <coupling-MMF>0.0</coupling-MMF>
    </mode-id-list>
            .
            .
            .
    </coupled-mode-list>
<MDL>12.0</MDL>
```

(a) Path 1

Path2 - Strong coupling

```
<coupled-mode-list>
    <mode-id-list>
        <id>1</id>
        <mode-id>m2</mode-id>
        <mode-id>m3</mode-id>
        <coupling-MMF>0.0</coupling-MMF>
    </mode-id-list>
            .
            .
            .
    </coupled-mode-list>
<MDL>8.0</MDL>
```

(b) Path2

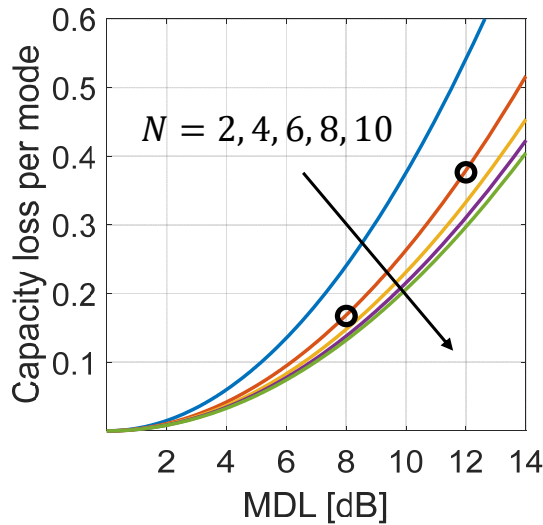Fig. 5: Details of the impairment-aware topology database in the strong coupling scenario for two different paths

Fig. 6: Capacity loss per mode versus average link MDL for $N = 2, 4, 6, 8$ and 10 strongly coupled cores [6]

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