Field trial of SDN-controlled probabilistic constellation shaping supporting multiple rates over a coupled-core multi-core fiber

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Abstract *A SDN controller configures probabilistic constellation shaping through NETCONF optimizing spectral efficiency according to the path length or degradations due to soft failure. The integrated data and control planes are demonstrated with multiple rates (800-850-900-950-1000Gb/s) in a field trial employing multi-core fiber with 4-coupled cores. ©2022 The Authors*

Introduction

Space-division multiplexing (SDM) based on parallel fibers, multi-core (MCFs), or multi-mode fibers (MMFs) is under investigation in support of traffic increase [1], and real-time transmission experiments have been recently reported [2][3]. Multiple-input multiple-output (MIMO) coherent receivers are used to extract the signals transmitted in the fiber modes in the regime of strong coupling, as well as to compensate for linear propagation effects, such as chromatic dispersion, modal dispersion and mode-dependent loss [4][5][6]. Networks based on SDM can thus leverage multiplexing over two dimensions: space and spectrum. In general, the usage of the spectrum can be optimized by adopting probabilistic constellation shaping (PCS) [7][8], which provides a fine trade-off between physical layer robustness (or more simply optical reach) and spectral efficiency by modifying the constellation based on the physical layer characteristics of a path. However, PCS has been mainly studied and demonstrated for transmissions or networks over single-mode fibers, whereas much fewer investigations [9] of its use in MCF- or MMF-based SDM systems have been reported, of which none using deployed fibers nor integration with Software Defined Control (SDN) plane.

In this paper, for the first time, we present a field trial where a Software Defined Networking (SDN) controller relies on the NETCONF protocol exploiting OpenConfig YANG data models [10] to configure constellation shaping in MIMO-based transceivers on the deployed SDM fiber infrastructure in the city of L'Aquila, Italy [11]. Measurements show that a set of dual polarization probabilistic shaped 32 quadrature amplitude modulation (PCS-32QAM) constellation with different entropy and shaping values enables multiple rates (cumulative on the total number of cores) of 800, 850, 900, 950, and 1000 Gb/s over a 4-core coupled-core MCF along 2800 km, 2450 km, 1960 km, 1400 km, and 700 km, respectively. Moreover, a soft failure is emulated and the experiment show that the reconfiguration of the shaping acted by the SDN controller permits to recover part of the traffic along the same path: 850 Gb/s of the original 900 Gb/s.

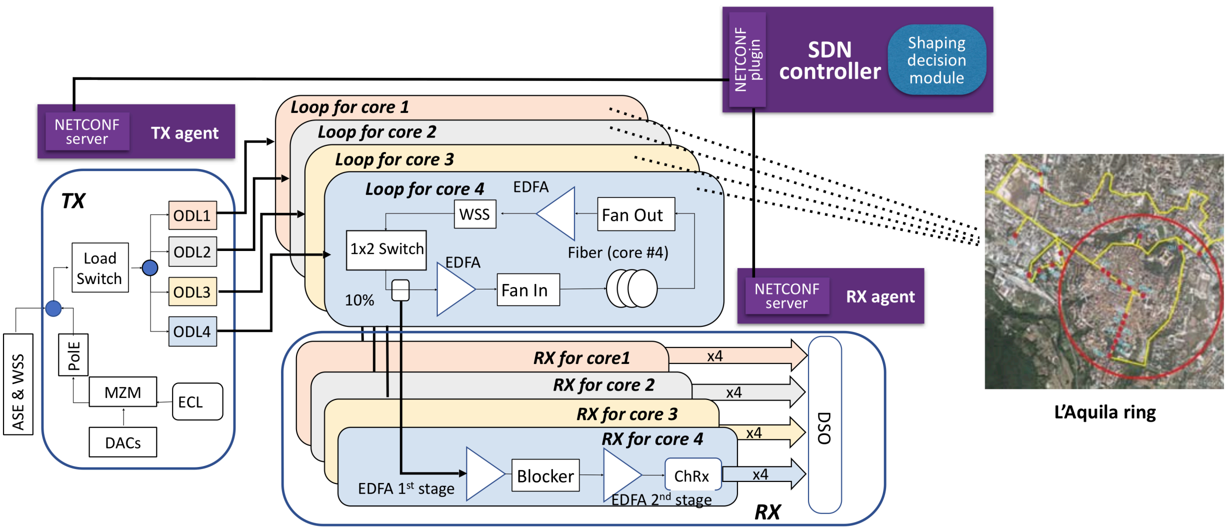

Fig. 1 Integrated data and control plane on field

Field trial set up

Fig. 1 shows the considered setup, including data and control planes and relying on a four-fold recirculating loop consisting of 11 concatenated 4-core coupled-core MCF fiber deployed in the city of L'Aquila, Italy within project INCIPICT [12]. The specs of the MCF fiber cable can be found in [11]. A custom-built SDN controller holding a NETCONF plugin is responsible for transceiver configuration through the NETCONF protocol [13][14]. The OpenConfig (OC) model [6] – encompassing a set of vendor-neutral YANG data models – is adopted to configure transceivers at both transmitter (TX) and receiver (RX) sides. In particular, the OC terminal device model defines optical channel configuration parameters such as the central frequency and the output power. Moreover, within the OC model, operational (OP) modes have been introduced to also enable vendor-specific parameters such as forward error correction (FEC) and to include proprietary advanced transmission solutions. In this paper, the agent maps the OP mode to one of the specific probabilistic shaping levels, which are reported in Tab. 1 together with their associated net rate *R* achievable by the two polarization and 4-cores coupled-core MCF optical system.

Table 1 OP mode, shaping coefficient (S), raw spectral efficiency (H), and net bit-rate (R)

OP mode	S (shaping)	H [bit/symb] [per core and polarization]	Overall net bit-rate R [Gb/s]
5	0.1132	4.17	800
4	0.0929	4.37	850
3	0.0724	4.58	900
2	0.0492	4.79	950
1	0	5	1000

Any intermediated bit rate between 800 Gb/s and 1000 Gb/s can be set with 50 Gb/s granularity by adjusting the entropy and shaping parameter (S) of a 30 Gbaud PCS-32QAM working with a FEC overhead of 20%. Upon connection request, the SDN controller selects the most spectral efficient shaping supporting the length of the computed path (*Shaping decision module* in Fig. 1). Then, the SDN controller sends a NETCONF <edit-config> message to both the TX and RX agents for TX and RX configuration. This message writes the transceiver configuration parameters values (e.g., central frequency, output power, and OP mode) selected by the SDN controller into the NETCONF server at each agent. Then, the agent interprets the configuration values, maps the OP mode to a specific shape, and configures the transceiver, loading the signal with the proper level of shaping into digital-to-analog converters (DACs).

At the data plane, the loop also includes four wavelength selected switches (WSS), configured as dynamic gain equalizing filters, and four two-stage single-mode amplifiers connected to the MCF fibre cores through fan-in and fan-out devices. A Channel Under Test (CUT) in the centre of the WDM comb is generated using a <100 kHz External Cavity Laser (ECL), modulated at 30 GBaud with a single-polarization Mach-Zehnder Modulator (MZM) driven by two 60GS/s DACs. Polarization multiplexing is emulated by splitting and recombining the optical signal over orthogonal polarizations (PolE). To mimic WDM transmission in full load condition, further 20 channels, 50 GHz spaced, are emulated by shaping ASE noise using a high-resolution WSS (Finisar Waveshaper). The maximum allowable power into the fan-in/fan-out devices limits the number of channels.

The whole WDM is then split into four paths and decorrelated with optical delay lines (ODL) with a relative delay of ~100 ns. The resulting signals are injected into the recirculating loop through solid-states 1x2 switches, while an additional load switch is used to improve the extinction ratio of the injected signals. A four-fold receiver is employed. For each core, the WDM signal is extracted from the loop, filtered (blockers) between the two stages of optical amplifiers and detected by a polarization-diverse coherent receiver (ChRx). The resulting 16 electrical signals are captured by a digital storage oscilloscope (DSO) operating at 80 GSa/s. Finally, signals are processed offline after down-sampling them to 2 samples per symbol. After performing chromatic dispersion and frequency-offset compensation, an 8x8 MIMO processing based on frequency domain equalization allows to demultiplex each of the 8 tributaries.

Experiments

The QoT figure of merit considered in the experiments is the generalized mutual information (GMI), defined as in [15]. A set of data valid for system provisioning is generated using a three-step method. First, the GMI measurements are performed for different recirculating loop distances and transmitted optical power. Fig. 2 shows the achieved GMIs (per core and polarization) for each shaping when varying the optical reach (with 0 dBm of transmitted power per channel). Note that the maximum GMIs in back-to-back (see Fig. 2), are slightly different from the theoretical maximum values (H of Tab. 1) because of the non-ideality of TX and RX components. Then, a specific GMI threshold (GMI_{th}) is considered for each shaping (Tab. 2). GMI_{th} is set 14% higher than the GMI threshold achievable with an infinite block-length ideal FEC with 20% overhead. In this way we consider penalties due to real FEC implementations. Based on Fig. 2 and GMI_{th}, the maximum optical reach (L_{max}) is derived for each shaping level and reported in Tab. 2.

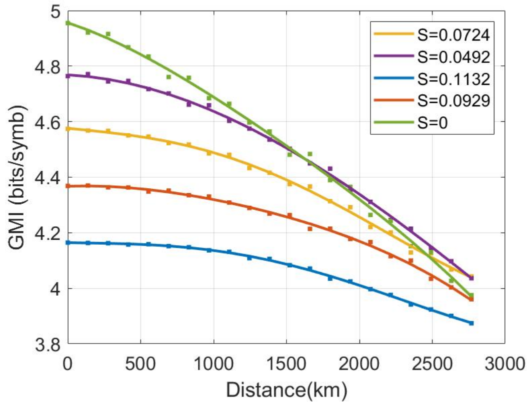

Fig. 2 GMI vs. distance

Table 2 GMI_{th} and optical reach (L_{max})

OP mode	S	GMI-TH	Lmax [km]
5	0.1132	3.8	2800
4	0.0929	4.0375	2450
3	0.0724	4.275	1960
2	0.0492	4.5125	1400
1	0	4.75	700

Then, provisioning is performed for a connection over a 1900-km path. Based on the derived optical reach values reported in Tab. 2, the *Shaping decision module* at the SDN controller selects the shaping supported by the path (S=0.0724). Thus, the SDN controller sends the <edit-config> message to the TX and RX agents. Fig. 3 shows the content of the control plane message: a central frequency of 193.9 THz and 0 dBm launch power are configured; OP mode 3 is set. Each agent maps the given OP mode to the correct shaping profile (see Tab. 2) to be loaded. The selected OP mode supports 900 Gb/s (Tab. 1) along the overall 4 cores and admits the required optical reach of 1900 km.


```
<components xmlns="http://openconfig.net/yang/platform">
  <component>
    <name>channel-1</name>
    <optical-channel xmlns="http://openconfig.net/yang/terminal-device">
      <config>
        <frequency>193900000</frequency>
        <target-output-power>0</target-output-power>
        <operational-mode>3</operational-mode>
      </config>
    </optical-channel>
  </component>
</components>
```


Fig. 3 <edit-config> message received by the TX agent

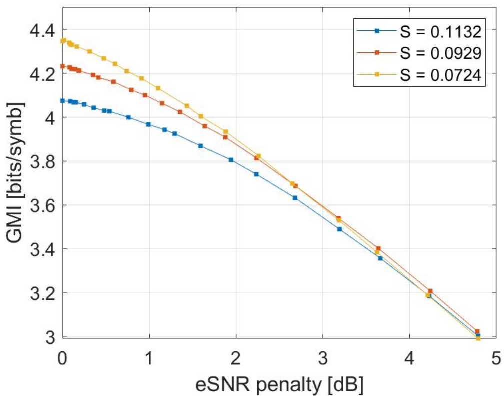

Fig. 4 GMI vs. eSNR penalty on a path of 1400 km


```
<?xml version="1.0" encoding="UTF-8"?>
<notification xmlns="urn:ietf:params:xml:ns:netconf:notification:1.0">
  <eventTime>2022-09-05T08:51:32.517635+00:00</eventTime>
  <failure xmlns=http://openconfig.net/yang/terminal-device>
    <port>channel-1</port>
    <reason>esnr</reason>
    <level>14.0</level>
  </failure>
</notification>
```


Fig. 5 <notification> message sent by the RX agent

Finally, soft failures are introduced along a path of 1400 km. Noise is artificially added at the transmitter side to mimic performance degradation (e.g., non-ideal transponder or amplifier). GMI and the electrical signal-to-noise ratio (eSNR) are measured at RX. Fig. 4 shows GMI decreasing with eSNR penalty. In the networking experiment, an eSNR penalty of 1dB (with respect to the original eSNR=15dB) is introduced to a signal with S=0.0724: the penalty creates unacceptable QoT, given that GMI decreases below the associated GMI_{th}=4.275 (see Fig. 4). The RX agent sends to the SDN controller a <notification> message (Fig. 5) implementing the alarm and reporting the measured eSNR. The SDN controller (through b2b characterization and the interpolation of values in Fig. 4) re-configures S to 0.0929, which is acceptable (the related GMI is above the associated GMI_{th}=4). This reconfiguration permits to recover 850 Gb/s of the original 950 Gb/s along the same path.

Conclusions

In this paper, we present the first field trial of a SDN-controlled PCS over SDM based on a deployed 4-core coupled-core MCF. Shaping values enable distance adaptation and multiple rates of 800, 850, 900, 950, and 1000 Gb/s. Based on characterization performed on the deployed transmission system, the SDN controller selects the shaping according to the required optical reach to provision a given connection. Shaping reconfiguration also permits to recover traffic upon soft failure.

Acknowledgements: This work has been financially supported by the Italian Government through project PRIN2017 “FIRST” (GA 2017HP5KH7 002) and project INCIPICT.

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