In-service Crosstalk Monitoring and Tracing for Short-Reach Space-Division Multiplexing (SDM) Optical Networks

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Abstract: We propose an in-service crosstalk monitoring and tracing method using fine-grained monitoring optical time slices for SDM-enabled intra-datacenter and HPC systems. Modal crosstalk below -36.01dB was successfully monitored and traced in an MMF transmission system.

OCIS codes: (060.4250) Networks; (060.4510) Optical communications;

1. Introduction

With the rapid growth of cloud services and emerging bandwidth-hungry applications, the traffic of intra-datacenter networks (intra-DCNs) and high performance computing (HPC) systems has sustained exponential growth in recent years, and this trend is expected to continue for the foreseeable future [1, 2]. However, previous studies [3] show that the transmission capacity over single-mode fibers (SMFs) is rapidly approaching its fundamental Shannon limit. To break through the capacity limit of single-core single-mode fiber, researchers focused on the dimension of space and proposed the concept of space-division multiplexing (SDM) by introducing multi-core fiber (MCF), few-mode fiber (FMF) and multi-mode fiber (MMF) into optical networks [4, 5]. It is proved that SDM enabled by MCF or MMF is able to enlarge the transmission capacity as well as reduce networks CapEx [6].

However, the introduction of MCF and MMF into optical networks also brings the inter-core/inter-mode crosstalk challenge, which destroys orthogonality among spatial channels [4]. In short-reach networks like intra-DCN or HPC, it is possible to achieve uncoupled SDM transmission, in which signals on each core/mode are transmitted as independent channel, and low-complexity DSPs for wavelength-division multiplexing (WDM) channel equalization in current SMF transmission systems are applicable. In uncoupled short-reach SDM networks, lightpath crosstalk need to be optimized below a threshold, which is related to the modulation format, baud rate, FEC ability etc. [7]. However, the level of lightpath crosstalk can change during network operations including the setup and teardown of WDM channels or spatial channels transmitted through neighboring cores or different modes, and other environmental fluctuations [8]. If the network controller cannot be aware of the changes of lightpath crosstalk and re-route some lightpaths for crosstalk reduction, the bit-error ratio (BER) of some connections may be unacceptable. Therefore, in-service crosstalk monitoring and tracing is necessary in short-reach SDM optical networks. A method for in-service crosstalk monitoring in point-to-point MCF transmission systems has been reported in literature [8]. But it is difficult to be applied in the more complex network scenarios since large amount of pilot tones (wavelengths) are required with complex operations.

In this paper, we proposed a novel in-service crosstalk monitoring method using fine-grained optical time slice monitoring channels for crosstalk reduction in short-reach SDM optical networks. Benefitting from the large amount of fine-grained channels provided by optical time slices switching (OTSS) [9], it becomes possible for every source node to allocate a dedicated monitoring time slice carrying the traffic and path information for each connection. Crosstalk monitoring and tracing can be realized by extracting the information contained in these monitoring time slices.

2. In-service crosstalk monitoring and tracing

To achieve in-service crosstalk monitoring and tracing, we allocate a fine-grained dedicated monitoring time slice for each data channel to simulate the crosstalk generated between the monitored data channel and its "neighboring" spatial channels. Fig. 1 illustrates the concept of the proposed in-service crosstalk monitoring and tracing method using fine-grained optical time slice monitoring channels in a 6-node fat-tree MMF-enabled intra-DCN.

An SDN controller is responsible for calculating and allocating available time slices for all the fine-grained monitoring channels. The monitoring time slices are transmitted periodically and their period is defined as the monitor period. The allocation of the monitoring time slices should obey the following three principles:

1) The monitoring channels and data channels are assigned different wavelengths.
2) The monitoring time slices for different traffics occupy different time slots.

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3) The monitoring time slices are transmitted along the exact same paths (same fiber links, cores and modes, etc.) with their corresponding traffic data.

The monitoring channels can be established by switching the monitoring time slices at each traversing node coordinately at the pre-set time points. Notice that all nodes are required to be time synchronized in the system.

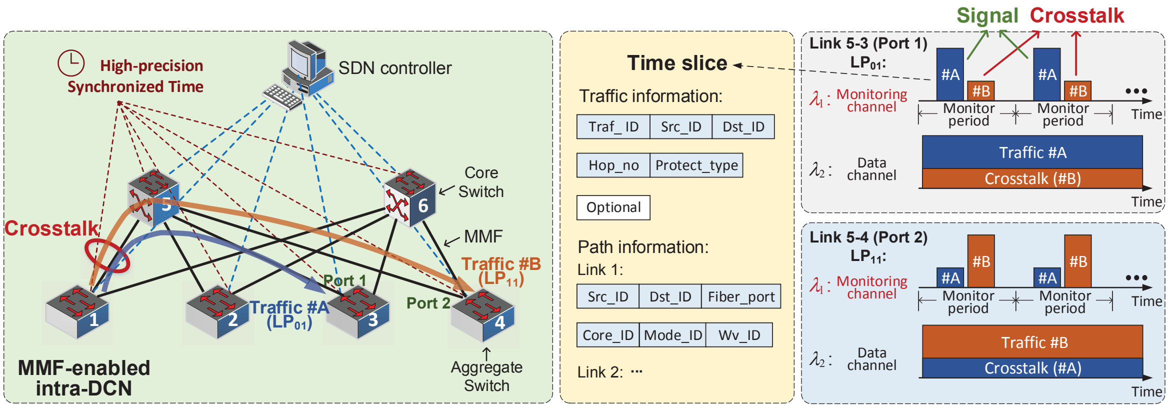


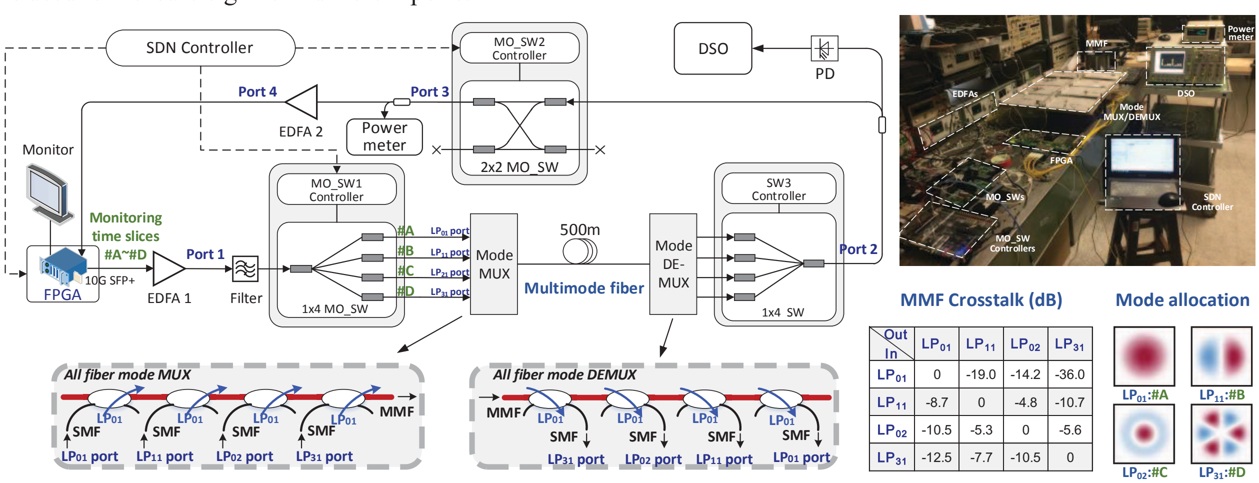
Fig. 1. Concept of in-service crosstalk monitoring and tracing

The monitoring time slices carry traffic and path information including traffic ID (*Traf_ID*), source node ID (*Src_ID*), destination node ID (*Dst_ID*), hop number (*Hop_no*), etc. By extracting the information contained in these monitoring time slices, in-service crosstalk monitoring and tracing can be realized.

For instance (Fig. 1), Traffic #A and Traffic #B are assigned to the LP_{01} and LP_{11} modes in the data channel (λ_2) of the MMF between Node 1 and Node 5, respectively. The monitoring time slices #A and #B are transmitted along exactly the same paths with their corresponding traffic data in the monitoring channels (λ_1). Crosstalk is generated between LP_{01} and LP_{11} in both of the monitoring and data channels on Link 1-5. At the receivers of Node 3 (Port 1) and Node 4 (Port 2), "crosstalk time slices" (#B and #A) will be received and the "crosstalk traffic information" can be extracted, making it possible to accurately trace the crosstalk.

3. Prototype experiment of in-service crosstalk monitoring and tracing

A prototype experiment is carried out to evaluate the performance of the proposed in-service crosstalk monitoring and tracing method. As shown in Fig. 2, a 500-m multi-mode fiber and all-fiber mode multiplexer/demultiplexer (MUX/DEMUX) consisting of cascaded mode-selective couplers [10] are applied to achieve MMF transmission. Four monitoring time slices (#A ~ #D) are generated by 10G SFP+ on the FPGA. The monitor period is set to 1 ms and the time length of each monitoring time slice is set to 100 µs. An SDN controller is responsible for dispatching configuration commands to two magneto-optic switch (MO_SW) controllers, and switching operations are triggered by MO_SW controllers at the pre-set precise time. MO_SW1 is used to switch the four time slices into different mode ports and MO_SW2 is used to extract the desired time slice to obtain the crosstalk information of the corresponding monitoring channel (mode). Besides, we also use a 1x4 switch (SW3) to select the channel (mode) to be monitored. A power meter is deployed to measure the powers of the monitoring time slices and a digital storage oscilloscope (DSO) is used to measure signals at different ports.



In \ Out	LP_{01}	LP_{11}	LP_{02}	LP_{31}
LP_{01}	0	-19.0	-14.2	-36.0
LP_{11}	-8.7	0	-4.8	-10.7
LP_{02}	-10.5	-5.3	0	-5.6
LP_{31}	-12.5	-7.7	-10.5	0

Fig. 2. Experimental setup

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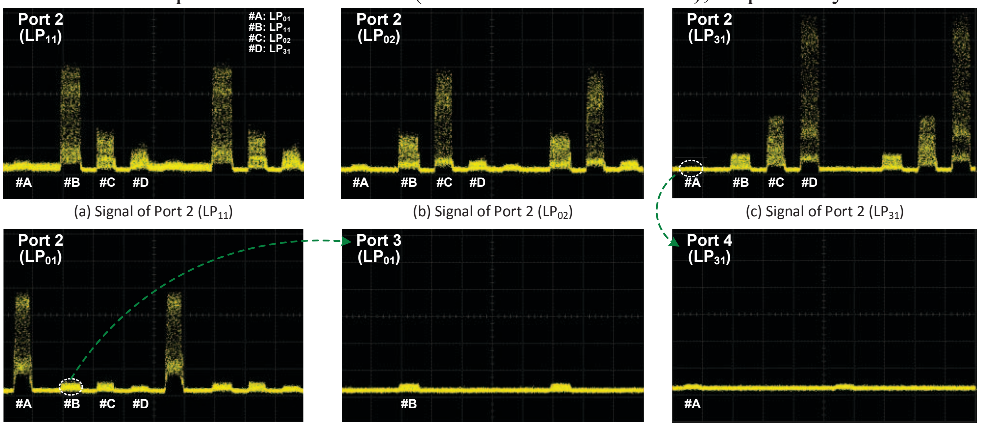
The mode allocation of the four monitoring time slices is also depicted in Fig. 2. Time slice #A ~ #D occupies LP_{01}, LP_{11}, LP_{02} and LP_{31}, respectively.

Figs. 3(a) ~ (d) present the DSO screen shots of the four mode monitoring channels at Port 2. Fig. 3(e) and (g) give the screen shots of time slice #B at Port 3 (after time slice extraction), and #A at Port 4 (after time slice extraction and amplification), respectively. The time length and power of the four monitoring time slices in mode LP_{01} are measured by the DSO at Port 2 and the power meter at Port 3 (after time slice extraction), respectively.



(a) Signal of Port 2 (LP_{11}) (b) Signal of Port 2 (LP_{02}) (c) Signal of Port 2 (LP_{31})

(d) Signal of Port 2 (LP_{01}) (e) Signal of Port 3 (LP_{01}) (f) Signal of Port 4 (LP_{31})

Fig. 3. DSO screen shots for monitoring channels

The main measured parameters of the received monitoring time slices in LP_{01} are presented in Fig. 4(a). In this measurement, time slice #A is the signal and the other three (#B ~ #D) are the crosstalk. All of the crosstalk time slices have also been received successfully by the FPGA placed at Port 4.

Time slices of Port 2 (LP_{01})

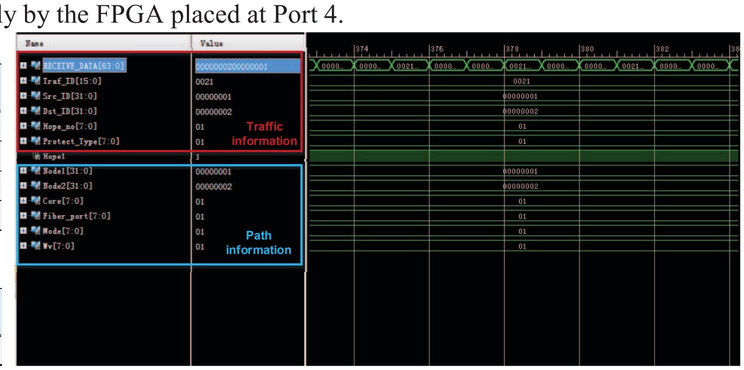
Time slices	Length (us)	Power (dBm)
#A	102.8	-7.59
#B	105.7	-16.33
#C	106.1	-18.12
#D	103.8	-20.04

(a)

Time slice of Port 3 (LP_{31})

Time slices	Power (dBm)	Crosstalk (dB)
#A	-41.51	-36.01

(b)



(c)

Fig. 4. Monitoring results: (a) Powers and lengths of time slices #A ~ #D at Port 2 (LP_{01}); (b) Power of time slice #A at Port 3 (LP_{31}); (c) Traffic and path information contained in time slice #A.

In order to explore how small the crosstalk can be monitored and traced, we select LP_{31} as the monitoring channel and extract the information contained in time slice #A. The power of time slice #A after extraction (Port 3) is -41.51 dBm and the waveform after amplification (Port 4) is shown in Fig. 3(f). After packet parsing, the traffic and path information contained in time slice #A can be successfully extracted as shown in Fig. 4(c). This result would indicate that small crosstalk below -36.01 dB (between LP_{01} and LP_{31}) can be successfully traced.

4. Conclusions

We propose a novel in-service crosstalk monitoring and tracing method using fine-grained optical time slice monitoring channels for short-reach SDM optical networks. To achieve this, we allocate a dedicated monitoring time slice which contains the traffic and path information for each traffic, and send it along the exact same path (in different wavelength channel) with their corresponding traffic data. Crosstalk monitoring and tracing can be realized by extracting the information contained in these monitoring time slices. We validate the proposed method by a prototype experiment and show that crosstalk below -36.01 dB can be successfully monitored and traced in an MMF transmission system.

5. References

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