Evaluation of Dynamic Skew on Spooled and Deployed Multicore Fibers Using O-Band Signals

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Abstract: We compare fluctuations of propagation delay and inter-core skew on spooled and field-deployed multicore fibers. Our observations show a reduction of propagation delay fluctuations over deployed fibers but similar inter-core skew behavior.

1. Introduction

The use of single-mode multi-core fibers (MCFs) has been extensively proposed for high-throughput and high-density short-reach optical interconnects to improve the performance of large-scale datacenters [1–3]. This approach is a good candidate to handle the bottlenecks in high-capacity switches along with MCF-based high density optical connectors, advanced low-loss and small footprint fan-in/out devices, and photonic integrated circuits for parallel transceivers [3].

A crucial criterion for the deployment of MCF-based optical interconnects is the skew between parallel optical lanes [4]. This skew results mainly from the transceivers electronics and optical propagation and is managed with electronic buffering techniques [5], which introduce electronic complexity and latency, with potential impact on cost. Nevertheless, skew management is critical to support latency-sensitive applications, such as 5G mobile networks. On MCF-based optical interconnects, the propagation-induced skew takes the form of differential propagation delay between cores, which we refer to as inter-core skew (ICS). This has been show to be at least one order of magnitude below that of equivalent single-core fibers [6], which may substantially relax the requirements on electronic buffering and reduce latency [3]. ICS may be characterized by a nearly constant static component and a dynamic time-varying component [4,6,7]. However, these studies have been performed using spooled fiber, which has been shown to strongly impact the ICS [4]. In fact, the evaluation of dynamic ICS in unspooled MCFs is yet to be performed, to the authors knowledge. For this purpose, we analyzed the skew characteristics of an 8-core MCF, deployed as part of INCIPICT experimental testbed in the Italian city of L'Aquila [8]. We report on the evolution of the dynamic ICS as well as on the fluctuations in propagation delay over a 24-hour period and compare the measurement results with equivalent measurements over spooled fiber. It is shown that propagation delay fluctuations in the deployed fiber are significantly reduced with respect to the spooled fiber. This behavior can be attributed to the unspooled MCF, but also to thermal insulation in the underground tunnel. It is also shown that the dynamic ICS behavior is relatively similar in both spooled and deployed MCFs. These observations may form a basis to support the future standardization of MCF-based optical interconnects.

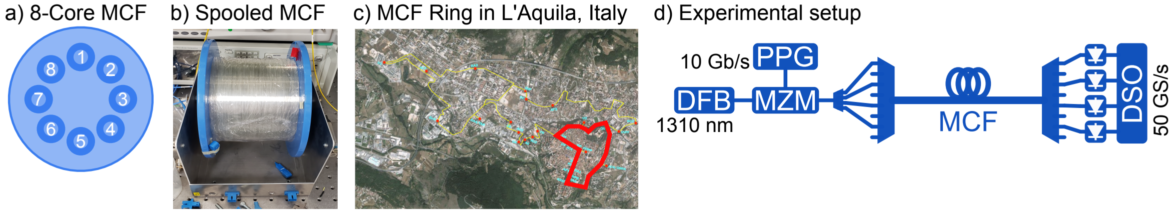

Fig. 1. MCFs under analysis. a) 8-core MCF profile. b) Photograph of one of the spooled MCFs. c) location of the fiber ring in the city of L'Aquila, Italy. d) Experimental setup for skew measurements.

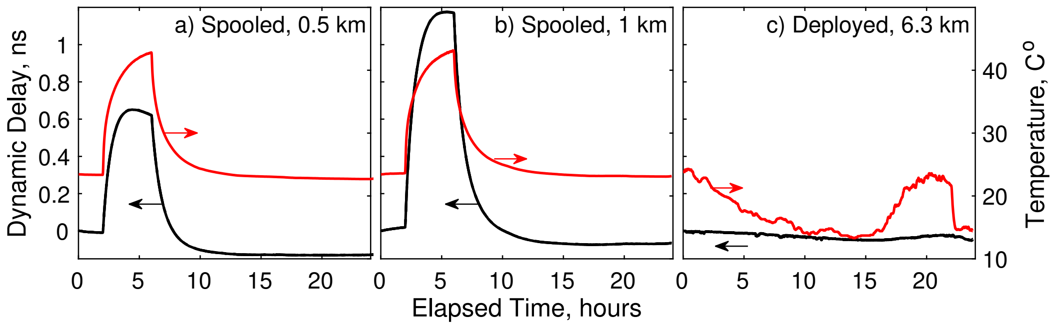

Fig. 2. Dynamic delay and temperature fluctuations in (a) 0.5 km and (b) 1 km of spooled MCF, and (c) in the 6.3 km deployed MCF.

2. Evaluation of Inter-Core Skew in Spooled and Installed Multicore Fibers

For this experiment, all MCFs were designed to operate in the O-band and had a cladding diameter of 125 µm. The spooled MCFs were similar to those described in [9], had 0.5 km and 1 km lengths and were spooled in approximately 8 cm diameter bobbins. They were homogeneous MCFs with 8 trench-assisted refractive index cores placed in a ring configuration with a 30.8 µm pitch, as shown in Fig. 1-a). The deployed MCF and corresponding cable were described in [8]. This was a 6.3 km 8-core MCF with trench-assisted cores placed in a ring configuration with 30.1 µm pitch. The MCF was installed in an underground service tunnel located in the south-west part of the city of L'Aquila, Italy, shown in Fig. 1-c). This was part of the fiber-optic test bed of the INCIPICT project [10].

Fig. 1-d) shows a simplified diagram of the experimental setup. This setup was used with all 3 considered MCFs. Light from a distributed feedback (DFB) laser operating at 1310 nm was modulated by a Mach-Zehnder modulator (MZM). The latter was driven by a pulse-pattern generator (PPG) to produce an on-off keying signal at 10 Gb/s. Four replicas of the modulated signal were produced with a power splitter and input into 4 ports of an 8-port laser-inscribed 3D waveguide fan-in. The selected cores were 1, 3, 5, and 7, shown in Fig. 1-a). Note that these were non-adjacent and correspond to the configuration considered for minimal crosstalk in bidirectional single-fiber transmission [7, 9]. The fan-in was connected to the MCF under analysis using 8-core SC-type connectors. The spooled MCFs were placed within a thermal chamber capable of increasing the temperature up to 45°C. The MCF output was spatially demultiplexed using another waveguide fan-out whose outputs were detected using 6.5 GHz bandwidth photodetectors (PDs). The PDs outputs were digitized at a digital sampling oscilloscope (DSO) operating at 50 GS/s. The DSO shared a time reference with the PPG, in order to accurately measure the relative arrival times of the detected signals. The dynamic propagation delay and ICS were estimated by first resampling the DSO traces by a factor of 200 to 1 TS/s. Cross-correlation was then used to estimate the propagation delay between signals. For the dynamic propagation delay, the arrival times of the signals were compared to those of the first observation of that signal. In the case of dynamic ICS, they were compared to the arrival time of the signal on core 1, used as reference.

Fig. 2 shows the dynamic propagation delays over a 24 hour period for all 3 considered MCFs. For the spooled MCFs, the temperature was increased from 23°C to 45°C and then back to 23°C. It is shown that the propagation delay follows the temperature changes closely. The increasing temperature gradient lead to an increase of the propagation delay of approximately 0.6 ns and 1.2 ns for the 0.5 km and 1 km MCFs, respectively. This corresponds to approximately 54 ps/km/degree and is in agreement with previous observations [6]. We note that this variation also includes the impact of heating the fiber bobbin. For the deployed fiber, it was not possible to vary the temperature of the tunnel. Instead, we used the average temperature in the city of L'Aquila, kindly provided in [11] and shown in Fig. 2-c). In this case, the propagation delay also followed the temperature changes although with a significantly reduced magnitude. Over the measurement period, propagation delay varied approximately 54 ps for a temperature gradient of about 11°. This corresponded to approximately 0.8 ps/km/degree, which was more than one order of magnitude smaller than in spooled MCFs. However, this difference is likely due to the insulation provided by the underground tunnel and the fiber cabling. Subsequent measurements of the temperature fluctuations within the tunnel have shown less than 1° fluctuations for outside fluctuations higher than 15°. In addition, a non-negligible 660 m section of the MCF cable was deployed in the laboratory room [8] and subject to temperature fluctuations induced by the measurement equipment.

Fig. 3-a) to -c) show the evolution of the dynamic ICS under the same conditions as in Fig. 2. In the case of the spooled fibers, we observed relatively small fluctuations, well within a 2.2 ps range, even when increasing the temperature up to 45°C. Similar behavior has been reported previously for spooled MCFs, generally presenting ICS

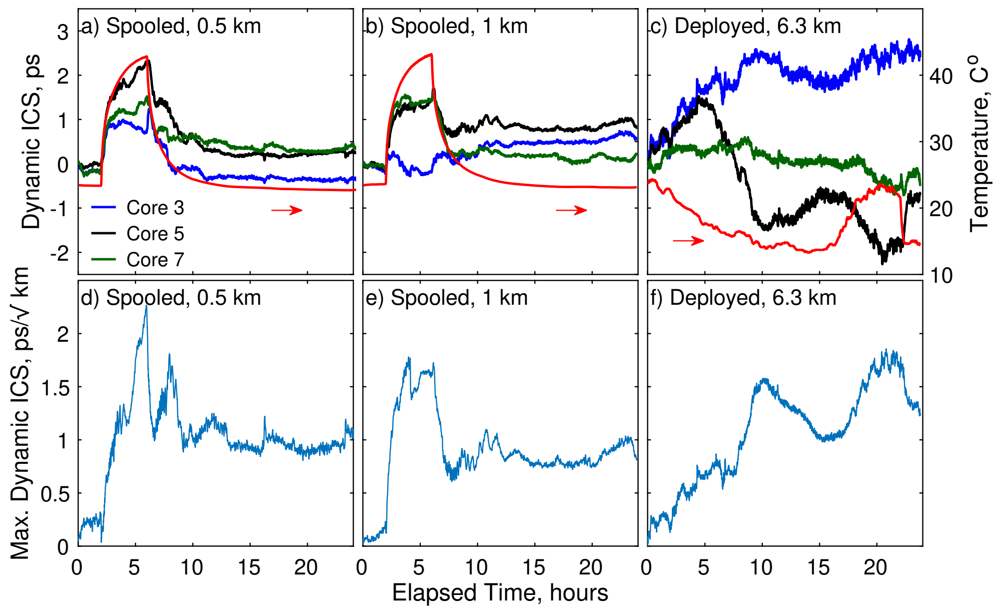

Fig. 3. Dynamic ICS and temperature measurements in (a) 0.5 km and (b) 1 km of spooled MCF, and (c) in the 6.3 km deployed MCF. (d)-(f) show the corresponding maximum dynamic ICS.

fluctuations within a few picoseconds [6]. In comparison, the dynamic ICS in the deployed fiber varied significantly with a maximum of approximately 5 ps between cores 3 and 5. This increase may be attributed to the increased fiber length. However, the scaling of the dynamic ICS with the fiber length is yet to be fully described. At this point, we will assume that its accumulation follows a random walk, scaling with the square root of the fiber length. Fig. 3-d) to f) show the evolution of the maximum dynamic ICS between any pair of cores, normalized to the square-root of the fiber length. This quantity has similar magnitude in all the considered fibers, which provides an indication that the installed fiber has similar dynamic ICS properties as the spooled fibers. However, we must stress that this observation is merely empirical at this point, while a formal description of ICS in MCFs is yet to be formulated, to the authors knowledge.

3. Conclusions

This work reported an experimental comparison between dynamic propagation delay and dynamic inter-core skew in spooled fibers and in fibers that were deployed in an underground tunnel in the city of L'Aquila, Italy. It was shown that both quantities are affected by the environmental temperature fluctuations. The fluctuations of the dynamic propagation delay in the deployed fibers were found to be smaller than in the spooled fibers by more than one order of magnitude, which we attribute to some thermal insulation provided by the tunnel and the cabling, as well as to the unspooling. In contrast, the dynamic inter-core skew was found to have similar properties in both spooled and installed fibers. Our observations have shown no significant impact of unspooling the fiber on this quantity.

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References

1. P. Winzer, D. Nelson, "From scaling disparities to integrated parallelism: A decathlon for a decade," J. Light. Technol. **35** (5), 1099 (2014).
2. B. Zhu, "SDM fibers for data center applications," OFC, M1F.4 (2019).
3. T. Hayashi *et al.*, "Multi-core fibers for data center applications," ECOC, M.1.D.6 (2019).
4. S. Li *et al.*, "Bending effects in multicore optical fibers," IEEE Photonics Conf., TuF3.2 (2013).
5. IEEE Std 802.3bs: Amendment 10: Media Access Control Parameters, Physical Layers, and Management Parameters for 200 Gb/s and 400 Gb/s Operation (2017).
6. B. Puttnam *et al.*, "Impact of temperature on propagation time and inter-core skew in a 19-core fiber," APC, S3K.4 (2018)
7. R. Luis *et al.*, "Dynamic crosstalk and skew on a 1.3 Tb/s full-duplex O-band short reach transmission," ECOC, Tu.1.A.3 (2019).
8. T. Hayashi *et al.*, "Field-deployed multi-core fiber testbed," OECC/PSC, PDP 3 (2019).
9. T. Hayashi *et al.*, "125-µm-cladding eight-core multi-core fiber realizing ultrahigh-density cable suitable for O-band short-reach optical interconnects," J. Light. Technol. **34** (1), 85 (2016).
10. C. Antonelli *et al.*, "The City of L'Aquila as a Living Lab: the INCIPICT Project and the 5G Trial," 2018 IEEE 5G World Forum (5GWF), pp. 410-415 (2018).
11. CETEMPS Weather Monitoring Center, University of L'Aquila, *http://cetemps.aquila.infn.it* (2019).