Unrepeated HCF Transmission over spans up to 301.7 km

A. Ali, Y. Hong, M. Kamalian-Kopae, S. Bakhtiari Gorajoobi, S. Bawn, B. Gholizadeh, J. Hooley, M. Alonso, B. Guan, Y. Yin, M. Tuggle, E. Numkam Fokoua, S.R Sandoghchi, S. Doran, C. Wallace, T. Pearson, D. J. Richardson, F. Rey, J. Gaudette, B. J. Puttnam

Microsoft Azure Fiber, Unit 7, The Quadrangle, Romsey SO561 9DL, UK. E-mail:abdallaha@microsoft.com

Abstract: We transmit real-time data-signals over HCF span-lengths reaching 301.7 km using a novel high-power (37 dBm) HCF line-system, achieving full C-band system data-rate of 25.6 Tb/s after 200.5 km with negligible fiber transmission penalty, demonstrating the potential of HCFs to expand unamplified links.

1. Introduction

Hollow-core fibers (HCFs) have become the focus of widespread research in recent years due to several attractive properties including optical loss below the lowest recorded in silica fibers, >30% lower latency and low chromatic dispersion [1]. Further, they have orders of magnitude lower non-linearity than glass-core fibers allowing higher launch powers and the potential to revolutionize optical transmission systems by extending the reach of unamplified network links without the need for Raman amplification and bringing cost and performance benefits.

Despite such interest and demonstrations of ultra-low loss over single fiber strands [2, 3], the challenge to produce long fiber draws and the need for further development of splicing, handling, monitoring and cabling has limited transmission demonstrations to comparatively short fiber links thus far. Here, we demonstrate how a maturing hollow-core fiber communications eco-system can exploit reducing HCF losses and high-launch power to extend the range of metro networks to the 100s of km scale. We employ a custom developed bi-directional HCF line system based around a 37 dBm output power EDFA and low-noise preamplifier (PA) with free space HCF connections. The rack-mounted system also has functionality for a newly developed long-range optical-time division reflectometry (OTDR) system with high peak pulse power to overcome the low HCF back scattering. In combination with real-time transceiver arrays, we construct an experimental transmission system to report a full system data-rate of 25.6 Tb/s after 200.5 km transmission and show the potential for further reach with lower link-loss or higher launch powers by transmitting some channels up to 301.7 km. For context, Fig. 1(a) summarizes single-span HCF transmission demonstrations previously reported in the scientific literature [4-8] before OFC'25. In order to compare studies with varying spectral bandwidths, the spectral efficiency (SE) is plotted against transmission distance with spectral bands and real-time vs offline processing demonstrations, further noting that in contrast to the previous studies using real-time transceivers, the results presented here use fully loaded independent data-channels as opposed to amplified spontaneous emission (ASE) noise as dummy channels. Figure 1 shows that the 200.5 km measurement achieved comparable spectral efficiency to previous real-time demonstrations, but with a nearly 10-fold increase of unrepeated transmission distance. These results show that the low non-linear impairment and low loss potential in HCF can allow extended unrepeated transmission without Raman amplification and revolutionize the design of future optical networks.

2. Experimental Set-up

The experimental set-up for the HCF transmission demonstration is shown in Fig. 1(b). An array of up to 32 commercial-grade real-time transceivers was used to transmit data over HCF spans ranging from 102.3 km to 301.7km. The transceiver cards used dual polarization probabilistic-shaped (PS) 16-quadrature-amplitude modulation (QAM) at a maximum of 138 GBaud and the baud-rate and shaping level set by the link conditions. The transceiver features soft-

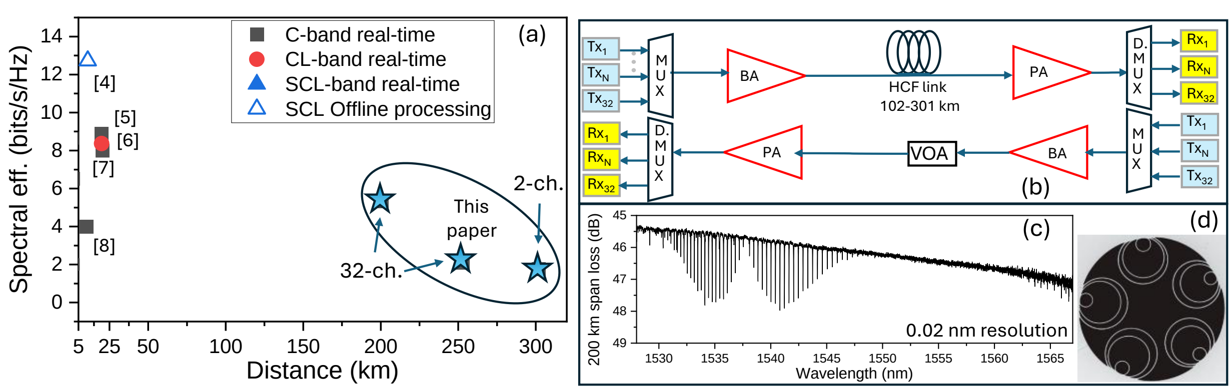

Fig. 1: Comparison of HCF single-span transmission demos > 5km before OFC'25 [4-8] showing SE per-direction (b) experimental set-up for extended metro transmission demonstration (c) 200 km span loss, and (d) profile of utilized DNANF fiber

decision - forward error correction (FEC) with 15% overhead providing 12-12.5 dB net coding gain. The modulated channels were combined in an arrayed waveguide grating based multiplexer (MUX) with 150 GHz channel spacing and 3-dB filter bandwidth of 140 GHz. The MUX output was directed to a high-power EDFA with up to 37 dBm output power that formed part of a custom designed bi-directional HCF line system. The high-power booster amplifier (BA) was co-located in a 1U 19-inch rack unit with a receiver PA, which also allowed for OTDR access to either fiber determined by an internal optical switch. The output of the rack unit was a duplex HCF patch cord to connect to the fiber pair under test. The test set-up used 102.3 km to 301.7 km of HCF in one direction and on the reverse path HCF-SMF connectors either side of a variable optical attenuator (VOA) to enable transmission penalty measurements.

The transmission fiber was based on a double-nested anti-resonant nodeless fiber (DNANF) design with 5 sets of nested resonator tubes with the fiber profile shown in Fig. 1(d) and is very similar in detailed structure and operation to the record low loss fiber reported in [2]. The fiber operates in the fundamental anti-resonant window and, as well as low fundamental mode loss, provides for low Inter Modal Interference (IMI) measured to be -60 dB/km for the 200.5 km spliced link. Figure 1(c) shows the loss profile of a 200.5 km link (measured using ASE noise) showing around 1.5 dB loss variation across the C-band. Gas absorption lines can also be seen on the signal spectrum at lower C-band wavelengths. This is attributed to the presence of carbon-dioxide (CO_2) in the fiber core and its impact on transmission performance is one of the aspects to be quantified in this study. The full 301.7 km link was made up of 57 bobbins of lengths ranging from 2 km to 17.9 km with average length of 5.3 km, a distance representative of field installations. The loss of each spool was measured using a cut-back method, described in [2], to be between 0.11 dB/km and 0.24 dB/km. However, we observed additional loss after transferring to the bobbins required for practical lab storage and splicing. The links were spliced with a power alignment technique with the loss estimated from OTDR to be 0.1 - 0.15 dB per splice. After transmission, real-time digital-signal-processing was performed to measure the pre- and post- FEC bit-error rates (BERs) as well as link monitoring values that could be extracted such as the instantaneous differential group delay (DGD), optical signal to noise ratio (OSNR) and chromatic dispersion (CD). Signal quality measurements were made at approximately 50 km intervals from 102.3 km to 301.7 km. In addition, at 200.5 km distance, long-term stable operation was confirmed by measurement of zero post-FEC errors over and an 8 hour period.

3. Results

Figure 2 shows OTDR measurements from each end the 200.5 km span obtained with 300 ns-wide optical pulses at 1550nm. The system was designed to compensate for the low HCF backscattering power and provided a spatial resolution of ≈44 m with a dynamic range (SNR = 1) >24 dB. The spikes show back-reflected power at splice points, and the total link loss of around 46 dB agrees with Fig. 1(c). We believe this represents the longest range of HCF OTDR with sub-50m resolution reported, paving the way for long-haul HCF link monitoring.

Figure 3 (a-e) summarizes the link and signal quality measurements after 200.5 km, the longest distance at which the full system data-rate of 25.6 Tb/s was measured. Figure 3(a) shows the channel spectrum after transmission showing a few dB power variation across all channels and the presence gas absorption lines on channels from 1532 nm until 1547 nm. Figure 3(b) shows the average DGD and CD for the received channels estimated from the DSP over 5 second periods. Interestingly, the DGD was under 5 ps for all channels. This low value is significant because it suggests that HCF system of this length could also be compatible with lower cost commercial transceivers such as those used in pluggable 400 ZR units. In addition, CD is also comparatively low compared to an equivalent SMF link ranging from 740 ps/nm at 1530 nm to just over 800 ps/nm at 1565 nm, equivalent to range of 3.8-4 ps/nm/km.

Figure 3(c) shows the pre-FEC BER and OSNR for all 32 measured channels after 200.5 km transmission and the pre-FEC BER with equivalent link-loss set on the reverse path. The receiver OSNR varied between 24.6 dB and 25.4 dB across all channels showing consistent performance across the entire C-band and this is reflected in the pre-FEC BER which is consistent around the 0.01 level. Strikingly, the VOA link loss control measurement is closely matched with only minor dissimilarity likely arising from variation in amplifier tilt. This shows that even at these high launch powers, no additional impairment arises from the HCF transmission channel, and the system is ASE limited. We also

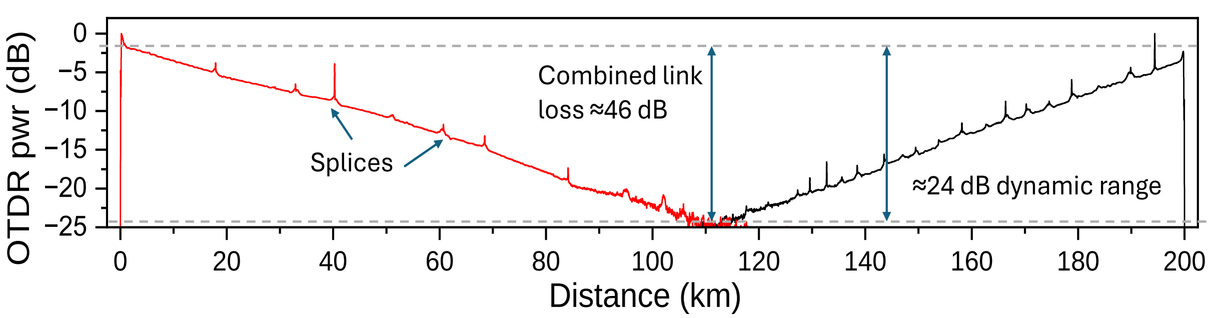

Fig. 2: OTDR traces from either end of 200.5 km span using 300ns pulses at 1550nm showing 24 dB dynamic range

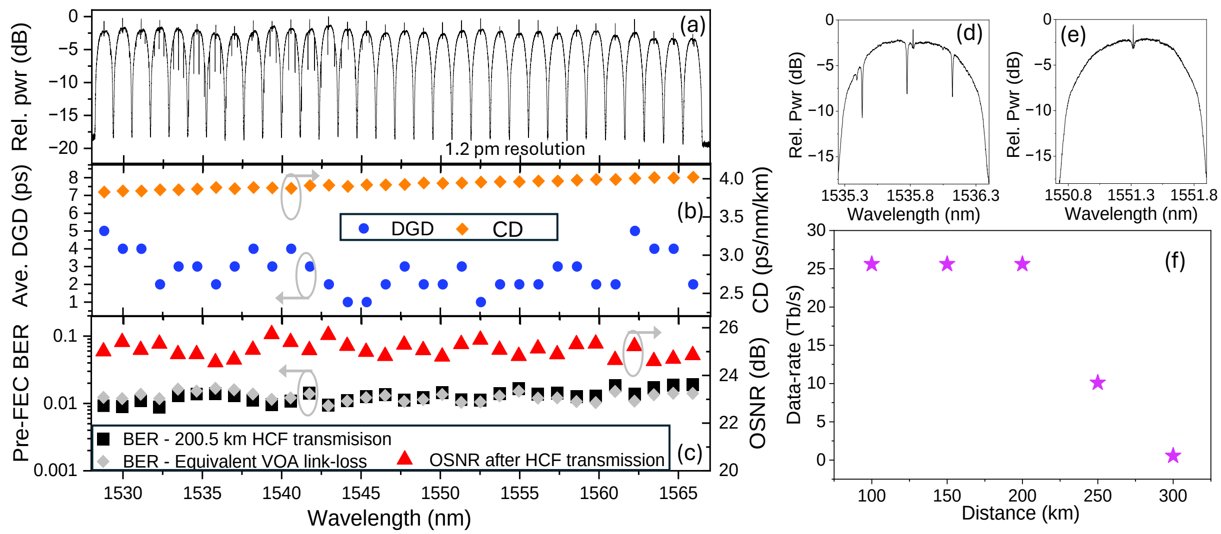

Fig. 3: (a) Received spectrum measured at 1.2 pm resolution (b) DGD and CD measurement summary and (c) OSNR and pre-FEC BER measurements after 200 km transmission and equivalent VOA link-loss, - individual channel spectra for (d) GLA impacted channel and (e) GLA-free channel, and (g) data-rate vs distance overall summary

note that even after 200 km transmission there is no discernible penalty from the gas absorption lines. Figures 3(d) and (e) show detailed channel spectra for a channel with strong gas-line features and one with minimal gas-line impact. Figure 3(d) show the gas-line depth of around 5 dB at this resolution, which is significantly lower than observed in previous generations of fiber and in contrast to previous studies [3]. This is a particularly significant result as it shows that HCF systems of this length are compatible with commercial C-band transceiver hardware bringing extended distance metro deployments into view.

Finally, Fig. 3 (f) shows the system data-rate vs transmission distance up to 301.7 km. The full system decoded data-rate of 32 x 800 Gb/s was achieved for 102.3 km to 200.5 km using 34 dBm booster output power to overcome the 46 dB link budget at 200.5 km. At 250 km, the end-to-end link loss increased to 57 dB, requiring maximum 37 dBm launch power and a reduction in the per-channel data-rates with a reduced SE modulation format, lower baud-rate and adapting the FEC overhead. The result of this was a reduced data-rate to 315.8 Gb/s per channel and 10.1 Tb/s system data-rate. At 301.7 km, the link budget reached over 70 dB and to investigate the limits of such a HCF system, two neighboring channels were each launched at 34 dBm, achieving a combined data-rate of 500 Gb/s.

We note there is scope for further reduction of the link loss to extend the achievable distances. Opportunities to further reduce splice and fiber losses remain and, in these measurements, the bobbins required for practical lab storage and splicing were observed to increase link loss by several dB. As illustrated by the 301.7 km measurement here, one further route for reach extension is to increase channel launch power through enhanced amplification technology, with potential for development in this area also possible outside of the C-band. Overall, our results show that maturing HCF technology offers a path to increased link lengths without Raman amplification and combined with low-latency, low DGD and low dispersion, can do this while reducing the need for high-specification transceiver technology.

4. Summary

We have demonstrated unrepeated HCF transmission over spans from 102.3 km to 301.7 km with a newly developed HCF eco-system and custom HCF line-system comprising of a 37 dBm booster amplifier and receiver pre-amplifier with HCF connections and functionality to accommodate OTDR-based link monitoring. We measure negligible transmission penalty and full system data-rate of 25.6 Tb/s after 200.5 km transmission. These results demonstrate that exploiting the low non-linear impairment and low loss properties of HCF can allow extended unrepeated transmission distances with the potential to radically alter the design of metro networks and inter-data-center connections.

References

[1] F. Poletti et al., ‘Towards high-capacity fibre-optic communications at the speed of light in vacuum’, Nat. Photonics, 7 (4), pp. 279–284, Apr. 2013,
[2] Y. Chen et al., ‘Hollow Core DNANF Optical Fiber with <0.11 dB/km Loss’, Proc. OFC’24, pp. Th4A
[3] Y. Xiong et al., ‘Field-Deployed Hollow-Core Fibre Cable With 0.11 Db/Km Loss’ Proc.ECOC’24 Th3B.8
[4] X. Liu et al., ‘502.6 Tbit/s S+C+L-Band Transmission in Anti-Resonant Hollow-Core Fiber’, Proc.ACP’24 Nov. 2024, pp. pp. ACPIPOC-0721-5
[5] B. Yan et al.,‘Towards Ultra-High-Capacity Long-Haul Fibre Communication: First Demonstration of Real-time 1.2Tb/s OTN Transmission at 3-Watt/Channel Launch Power over 20-km AR-HCF’, Proc ECOC’24 paper Th1B.1
[6] L. Feng et al., ‘Record Real-Time 2Pbit/s·km Transmission Over 20km HCF Using Widened C+L 12THz Bandwidth and 1.2Tbit/s Transponder with Symbol Rate of 135GBaud’, Proc.ACP’24 Nov. 2024, pp. paper ACPIPOC-0721-5
[7] A. Saljoghei et al., ‘First Demonstration of Field-Deployable Low Latency Hollow-core Cable Capable of Supporting >1000km, 400Gb/s WDM Transmission’, arXiv: arXiv:2106.05343. doi: 10.48550/arXiv.2106.05343
[8] M. A. Iqbal et al., ‘First Demonstration of 400ZR DWDM Transmission through Field Deployable Hollow-Core-Fibre Cable’, Proc. OFC’21 pp. F4C.2