C + L-Band Seeded Comb Regeneration for MCF Networks

B. J. Puttnam⁽¹⁾, R. S. Luis⁽¹⁾, G. Rademacher⁽²⁾, G. Di Sciullo^(1,3), M. van den Hout^(1,4), J. Sakaguchi⁽¹⁾, C. Antonelli⁽³⁾, C. Okonkwo⁽⁴⁾, and H. Furukawa⁽¹⁾

⁽¹⁾ NICT, 4-2-1, Nukui Kitamachi, Koganei, 184-8795 Tokyo, E-mail:ben@nict.go.jp
⁽²⁾ INT, University of Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany.
⁽³⁾ University of L'Aquila and CNIT, 67100, L'Aquila, Italy.
⁽⁴⁾ Eindhoven University of Technology, The Netherlands

Abstract We demonstrate C+L-band optical-frequency-comb regeneration from seed-signals that can be split, amplified, and transmitted over a novel metro/DC network architecture. Multi-core-fiber seed and data distribution with spatial-switching enables identical network-wide transceiver combs and ≈100 Tb/s/core and 600 Tb/s per-fiber data-rates. ©2023 The Authors

Introduction

Increasing demand for high-throughput data services has led to exploration of networks incorporating both wideband wavelength-division (WDM) space-division multiplexing and multiplexing (SDM) [1]. In such networks, parametric optical frequency combs (OFCs) [2] have a unique capability to provide hundreds of high-quality carriers over large bandwidths in a single device that has enabled both high channel count WDM [3] and petabit/s SDM transmission [4-6]. OFCs may also be remotely seeded. allowing coherent regeneration of identical combs that may act as local oscillators (LOs) for coherent reception. The identical frequency and coherence between transceiver comb lines may then be exploited by shared digital signal processing (DSP) [7-13], potentially reducing cost and complexity. Such regeneration has been performed over single fiber spans with moderate (11 nm) bandwidth per transmitted seed [8], but the potential of this approach to reduce the costs of wider coherent interconnects is also attractive for cost-sensitive applications, such as inter-data center (DC) networks.

Here, we demonstrate regeneration of wideband OFCs from a network broadcast seed signal. The seed may be regenerated, split, amplified, switched and transmitted over multiple hops before regenerating an identical LO comb with minimal impact on transmission quality. Using novel parametric OFCs with < 4 dB power

variation over an 80 nm bandwidth covering C and L-bands and functionality to generate or receive seed signals, we implement an SDM network architecture applicable to metro or inter-DC networks. The scheme, depicted in Fig. 1-(a), connects all nodes with weakly-coupled multicore fibers (MCFs) and adopts spatial switching to dynamically assign cores for data and seed distribution. In the seed layer, nodes may amplify, split and regenerate seed signals which allow OFCs to generate identical transmission carriers and LOs anywhere across the network.

We experimentally evaluate 4 scenarios (SCs) showing that the signal quality of 370 polarization-division multiplexed (PDM) 64quadrature-amplitude modulation (QAM) WDM-SDM signals covering nearly 80 nm bandwidth can be maintained after multiple switching stages and distances up to 130 km with a data-rate ≈100 Tb/s per spatial channel with a maximum of 600 Tb/s in 7-core MCF links. In addition to being the first demonstration of wideband comb regeneration from a network broadcast seed. these results show that combining OFCs and MCFs can enhance network functionality, significantly reduce transceiver hardware and potentially reduce costs through lower complexity DSP techniques by exploiting the coherence between hundreds of carriers and LO comb lines.

Node Description and Network Concept Figure 1(b) shows a diagram of the OFC. A



Fig. 1: (a) Overview of seeded-comb network showing seed and data layers over MCF connected nodes(b) diagram of wideband optical frequency comb (OFC) and (c) optical spectra of transmitted and regenerated comb 28 km MCF



SDM Mux/DeMux → = C/L-band EDFA
Seed core ○ (○) = data core (Bi-Di)
Fig. 2: (a) Set-up for transmitter and receiver used for signal quality measurements and scenario schematic and data-rate summary for (b) SC1, 6-core + seed transmission (c) SC2, bi-directional transmission 2 x 3-cores of 7-core fiber with comb regeneration using transmitted seed wavelength

stabilized RF oscillator generates 25 GHz spaced tones on a seed lightwave, which are broadened by a parametric fiber mixer. The seed laser is either a free running <1 kHz linewidth laser (master configuration) or a laser injection-locked (IL) to a reference seed (slave configuration). In slave operation, the laser locks to the reference seed to generate a comb with identical carrier frequencies which can allow coherent reception without frequency offset compensation. Fig. 1-(c) shows comb spectra for master and slave combs after 28 km seed transmission with insets showing individual lines from both combs at 3 points across the 80 nm spectrum.

All network nodes are connected by multi-core fibers (MCFs) which are used for data and seed distribution. The nodes in the seed distribution layer contain an OFC that may be operated in master or slave mode to provide carriers both for modulation and to act as LOs for coherent detection. They may also be able to switch, amplify, split, and regenerate the seed lightwave. Regeneration is achieved using injection locked slave lasers, similar to those used on the OFCs in slave mode operation.

Implementation and Evaluation

The feasibility of the network concept was investigated using various scenarios of seed and data transmission, including seed amplification and splitting, seed regeneration, bi-directional transmission and multi-hop operation with up to 130 km fiber transmission. A large optical switch was used as a switching cross-connect (SXC) between a number of MCFs with 4 or 7 cores. The switch was used to route signals through fibers, amplifiers, splitters and seed regenerator lasers used in data and seed distribution in 4 network scenarios (SC 1-4), outlined in Fig. 2 and Fig. 3.

In each scenario, optical transmission quality was assessed using the comb transmitter and receiver set-ups shown in Fig. 2-(a). C + L-band transmission from 1527.6 nm to 1606.2 nm was

based on a custom OFC by RAM Photonics, using principles described in [2, 3]. The OFCs had a seed wavelength of 1558.98 nm and generated 25 GHz spaced carriers with >45 dB OSNR. A tunable filter was used to create a sliding 3-channel band comprising test and neighbor channels which were separated from each other in optical interleavers (INT). Signal modulation used dual-polarization IQ-modulators (DP-IQ) driven by four arbitrary waveform generators (AWGs) operating at 49 GS/s. These produced 24.5 GBd, PDM-64QAM root-raised cosine shaped signals with a roll-off of 0.01 based on 2¹⁶-1-bit random binary sequences.

Modulated dummy wavelength channels were also generated from the OFC with optical processors (OPs) were used to both flatten the resulting spectrum and carve a sliding notch to accommodate the tunable test-band. The combined test and dummy band was then amplified and split for dummy spatial channels before fiber transmission with \approx 20 dBm total launch power per core.

At the receiver, the polarization of the comb seed was adjusted to the required input polarization with an active polarization tracker before being passed to an OFC for use as LO with the seed power between -7 and -11 dBm. It was assumed all nodes had access to a network distributed 10 MHz reference. The signal receiver path consisted of amplification stages on either side of a 0.4 nm tunable band pass filter centred on the test-channel with a VOA for power adjustment. A coherent receiver (CoRx) detected the signals which were then digitized by an 80 GS/s real-time oscilloscope for offline processing. The throughput of each wavelength channel was estimated from the generalized mutual information (GMI) and independently assessed using LDPC codes, similar to [14]. Signal quality and data-rate measurements were performed on three 10 µs traces for each wavelength and spatial channel in turn.



Fig. 3: Scenario schematic and data-rate summary for (a) seed amplification and switching over 2 MCF spans and (b) seed regeneration, amplification and switching with 130 km MCF transmission

Results

Figures 2-(b-c) and 3 depict the 4 network scenarios (SC 1-4) evaluated, each with a summary of measured GMI and decoded datarate (averaged over each of the utilized spatial channels) as a function of wavelength. SC 1 and SC 2 demonstrate point-to-point (P2P) data and seed transmission over a 28 km span of 7-core MCF. SC1, illustrated in Fig. 2-(b), uses 6 of the cores for data-transmission with 1 core reserved for seed transmission. SC2, depicted in Fig.2-(c), explores bi-directional (Bi-Di) transmission with the master and regenerated comb outputs at either end of the MCF both split to provide carriers for modulation and LO lines for 3 cores each. In both of these scenarios, the total data rate, estimated from the GMI is over 100 Tb/s per spatial channel with decoded throughput 4-5% lower. The total data-rate of SC1 was over 600 Tb/s and 2 x 300 Tb/s for SC2, showing the potential for the proposed network scenario to support high-capacity transmission.

Fig. 3 summarizes the remaining 2 scenarios exploring seed and data distribution across network nodes. SC 3, summarized in Fig 3(a), shows an amplified seed within a switching node after 28 km, 6-core + seed MCF transmission. Within the node, the amplified seed is split 8 times demonstrating the potential for seed sharing within high-order switching nodes. In this example, of the 8 seed copies, two are further transmitted, each with 3 of the ingress data cores for additional transmission over separate 4-core fibers with 36 km and 39 km lengths. Reception after multi-span transmission with LO from regenerated combs showed only a small 1 % reduction in per-core data-throughput compared to P2P transmission.

SC4, shown in Fig 3(b), explores multi-hop

seed and data transmission. At the first node, after 28 km 6-core + seed MCF transmission, 3 data-cores are dropped and received with a regenerated comb-based LO receiver and 3 more are further transmitted with the seed over an additional 56 km 4-core MCF. Included in the seed path of the first switching node is an IL laser regeneration stage while the second switching node again amplifies and splits the seed before final transmission of the 3 data-cores and seed over a final 45 km 4-core fiber. SC4 shows that even with 2 switching stages and a total of 130 km transmission, negligible reduction in the achieved data-rate is observed. Indeed, the percore data-rate of the 3 spatial channels dropped at the first switching node is only 2.7 Tb/s higher than those transmitted over 3 spans.

In all scenarios, data processing revealed reduced phase noise from Tx and LO comb coherence and negligible frequency offset on all channels showing potential for reduced DSP resources to be fully explored in future work.

Summary

We have demonstrated regeneration of identical wideband parametric optical frequency combs (OFCs) from a single wavelength seed for the first time. Further, we show how such a seed maybe amplified, split, switched and regenerated in a range of network scenarios. These results show that adopting OFCs can exploit the parallel spatial channels in MCF networks to reduce cost and improve optical network functionality by allowing generation of hundreds of high-quality locked carriers in a single device across the network. This enables high data-rate coherent transmission with the opportunity to exploit carrier coherence for reducing and sharing DSP resources as well as lowering hardware costs.

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