A point-to-multipoint flexible transceiver for inherently hub-and-spoke optical access networks

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***Abstract*—Using cascaded IFFT/FFT-based multi-channel aggregation/de-aggregation and orthogonal digital filtering, P2MP flexible transceivers operating in an 'add-as-you-grow' mode and offering additional physical-layer security are proposed and experimentally demonstrated in upstream 55.3Gbps@25km IMDD PONs.**

Keywords—point-to-multipoint (P2MP) transceivers, multi-channel aggregation, digital orthogonal filtering, intensity modulation and direct detection (IMDD)

I. INTRODUCTION

Present optical access networks such as PONs and 5G X-hauls are inherently hub-and-spoke, where a large number of spoke nodes are often connected to a single hub node [1]. Representative conventional optical technologies offering a point-to-point (P2P) connection between two locations always utilize two P2P transceivers operating at same predefined speeds [1]. However, to meet the stringent dynamic requirements of 5G and beyond mobile networks in terms of bandwidth, flexibility and latency, the existing P2P technologies are expensive due to their inefficient network resource utilization [2]. To effectively solve the technical issue, point-to-multipoint (P2MP) transceivers are highly desirable, which allow a large number of low-speed spoke transceivers to communicate with far fewer high-speed hub transceivers [3]. In comparison with the P2P transceivers, such P2MP transceivers also reduce the required hub transceiver count by ~50%, eliminate intermediate packet aggregation stages and decrease power consumption and footprint, thus resulting in >70% reductions in CapEx and OpEx [3]. Furthermore, it can also provide fast P2MP logical connectivity over arbitrary physical network topologies and has seamless adaption to variations in bandwidth demands and traffic patterns. XR Optics based on coherent technologies and digital subcarrier multiplexing offers a coherent solution for realizing such P2MP transceivers [3]. However, installed optical access networks are dominated by IMDD technologies, indicating that the XR Optics technology is not applicable in such application scenarios.

To effectively address the above technical challenge, in this paper, a novel P2MP flexible transceiver is proposed and experimentally demonstrated in an upstream 55.3Gbps@25km IMDD PON. This transceiver incorporates a new cascaded IFFT/FFT-based multi-channel aggregation/de-aggregation technique and an orthogonal digital filtering technique to allow each ONU to dynamically transmit an arbitrary number of channels according to actual user requirements. The orthogonal digital filtering technique is used to locate each ONU upstream signal at a desired radio frequency region and enables gapless upstream signal transmissions with negligible inter-ONU channel interferences [4]. Compared with the coherent XR Optics technique, this technique not only maintains the XR Optics-associated advantages but also possesses new features including: 1) flexible variations in both ONU count and ONU-accommodated channel count, which have the potential of operating in an 'add-as-you-grow' mode, 2) inherent physical-layer data transmission security by preventing eavesdroppers to illegally separate aggregated channels from a specific ONU without the knowledge of adopted transceiver DSP configurations, 3) excellent compatibility to existing multiplexing techniques (TDM, WDM, etc) and optical modulation/detection schemes (IMDD and coherent).

II. OPERATING PRINCIPLE OF P2MP FLEXIBLE TRANSCEIVERS

To detail the operating principle of the proposed P2MP flexible transceivers and to explore their performances, in this paper, more challenging PON upstream transmissions are considered only. In each ONU, for example, the k-th ONU, a novel DSP-enabled multi-channel aggregation technique outlined below is used to aggregate R channels employing cascaded (R-1) IFFT operations, as seen in Fig. 1(a). From the figure, it can be seen that, to aggregate the i-th channel, the (i-1)-th IFFT operation requires an IFFT size of $2W=2^{i-1}N$, where $2N$ is the size of the first IFFT operation. As depicted in Fig. 1(b), assuming the two signals to be aggregated by the (i-1)-th IFFT operation are A=[a_0, a_1,…, a_{W-1}] and B=[b_0, b_1,…, b_{W-1}], the IFFT input should be:

$$S_{in}=[a_0+b_0,\ldots, a_{W-1}+b_{W-1}, a_{W-1}^*-b_{W-1}^*,\ldots, a_0^*-b_0^*] \quad (1)$$

where * stands for the conjugate operation. After multi-channel aggregations in the k-th ONU, the real and imaginary parts of the produced upstream signal containing R channels are digitally up-sampled by a factor of M_k and then digitally filtered by an orthogonal digital filter pair [4]. The orthogonal digital filtering operations locate the produced ONU upstream

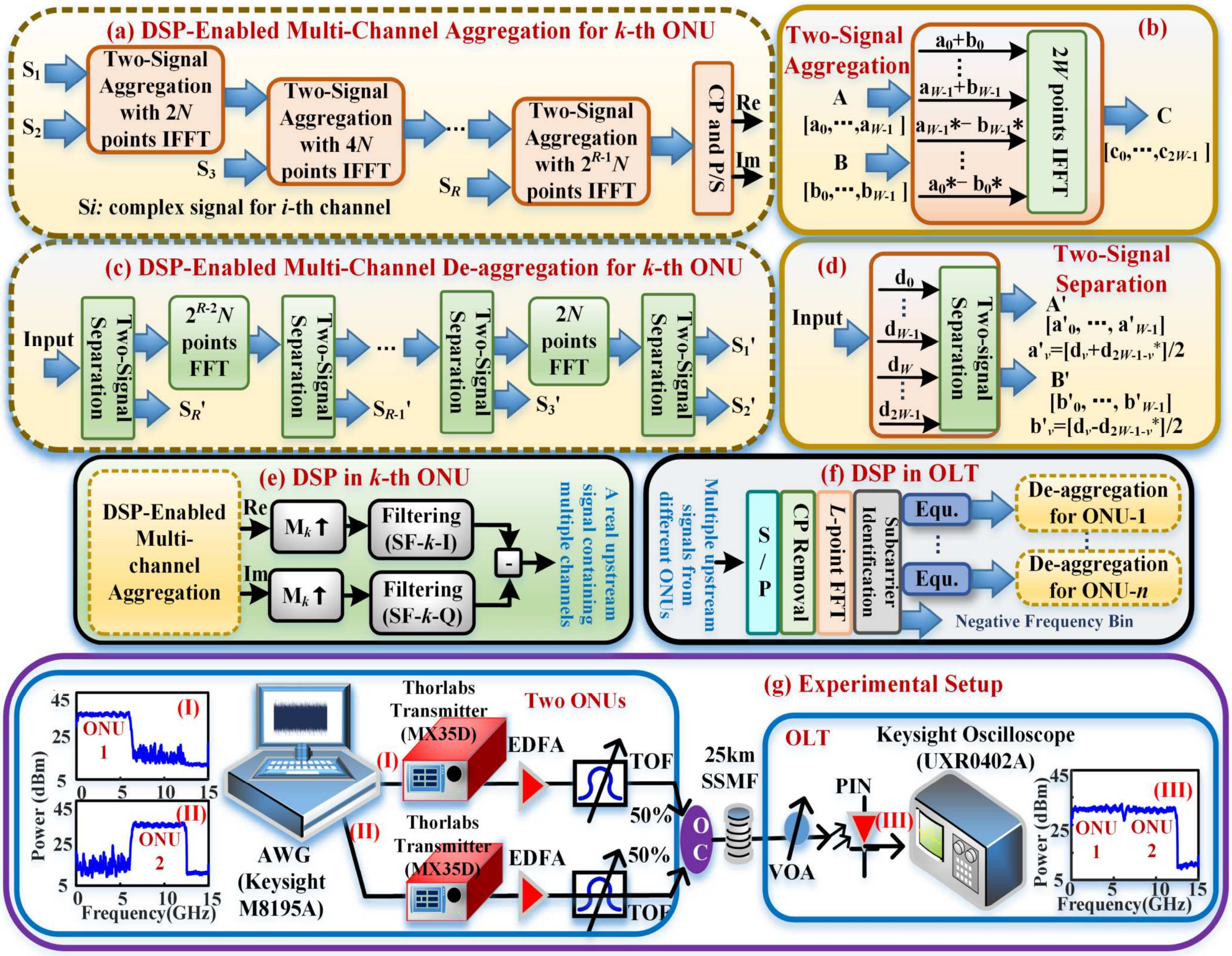

Fig. 1 Experimental setup of a 55.3Gbps@25km upstream IMDD PON incorporating P2MP flexible transceivers.

signals at desired radio frequency regions and enable gapless upstream transmissions by mitigating out-of-band radiations of the upstream signal produced by each ONU.

In the receiver DSP, after S/P conversion and CP removal, the FFT operations are performed to separate all ONU upstream signals. For the k-th ONU, its required FFT size is $L= M_k \cdot P$, where $P=2^{R-1}N$ is the size of the last IFFT operation involved in the k-th ONU transmitter. If all of the ONUs require the same FFT sizes, a single FFT operation is sufficient to separate all upstream signals from these ONUs. When different ONUs require different FFT sizes, multiple FFT operations each corresponding to a specific FFT size are required to be implemented following the procedures reported in [5]. Then, the ONU subcarrier identification process and the equalization process both reported in [6] and the multi-channel de-aggregation process shown in Fig. 1(c) are successfully performed for each ONU. As seen in Fig. 1(c), for the k-th ONU, separating R channels requires implementing (R-1) two-signal separation operations and (R-2) FFT operations. To separate the i-th channel, as depicted in Fig. 1(d), the input of the corresponding two-signal separation operation is $[d_0,.., d_{W-1}, d_W,.., d_{2W-1}]$. At its output, the two signals of $A'=[a'_0,.., a'_{W-1}]$ and $B'=[b'_0,.., b'_{W-1}]$ can be obtained by:

$$\begin{cases} a'_v = [d_v + d^*_{2W-1-v}]/2 \\ b'_v = [d_v - d^*_{2W-1-v}]/2 \end{cases}, v = [0,1,..,W-1] \quad (2)$$

III. EXPERIMENTAL DEMONSTRATIONS OF AN UPSTREAM IMDD PON INCORPORATING P2MP FLEXIBLE TRANSCEIVERS

A. Experimental Setup

The upstream experimental setup of an upstream 55.3Gbps@25km IMDD PON incorporating the proposed P2MP flexible transceivers is illustrated in Fig. 1(g), where two ONUs are considered. In each ONU, four independent channels are aggregated by implementing three cascaded IFFT operations with their IFFT sizes of 16/32/64. A CP ratio is 1/16. The two ONUs' up-sampling factors are 4. A Hilbert-pair approach is used to produce the digital filter pairs [4]. The digital filter length is 16 and the excess bandwidth factor is 0. Subsequently, a 1.2× digital oversampling operation, a digital-domain time delay operation, and a signal clipping operation with a clipping ratio of 12dB are performed for each ONU [7]. At the outputs of a 30GS/s@8-bit dual-channel AWG, each of the produced two upstream signals has a spectral bandwidth of 6.25GHz and an amplitude of 900mV. Their spectra are respectively illustrated in Fig. 1(g). Each upstream signal contains four independent channels each with modulation formats adaptively varying from BPSK to 64-QAM. For ONU1 (ONU2), the bitrates of its involved four channels are 3.4/3.4/6.6/14.8Gbit/s (3.4/3.4/6.2/14.1Gbit/s), thus resulting in an aggregated ONU bitrate of 28.2Gbit/s (27.1Gbit/s). The total upstream bitrates are 55.3Gbit/s over a 12.5GHz spectral region. Following the AWG, two transmitters each

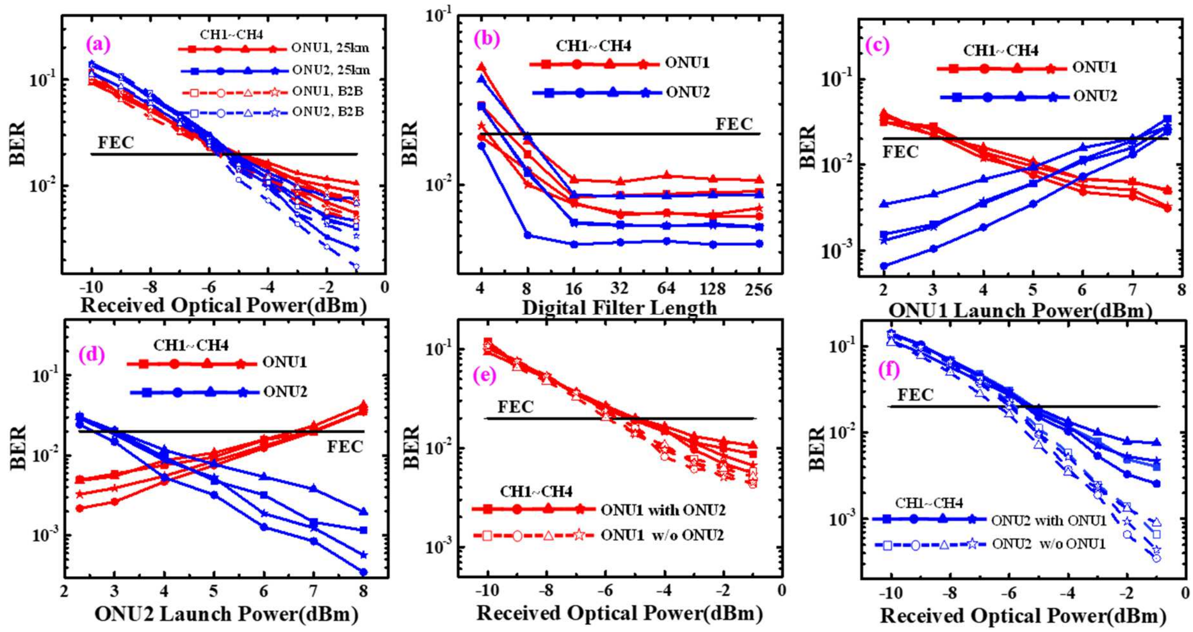

Fig. 2 (a) B2B and 25km upstream transmission performances; (b) digital filter length versus BER performances for ROPs of -2dBm; (c) and (d) ONU1 and ONU2 launch power dynamic ranges for ROPs of -2dBm; (e) and (f) channel interferences between different ONUs.

incorporating a 15kHz linewidth laser and a 35GHz MZM are employed to perform intensity modulation. The two ONU wavelengths are 1564.6nm/1565.4nm respectively. Two EDFAs each followed by a 0.8nm bandwidth optical filter fix the ONU output optical powers at 5dBm.

In the OLT, after a 40GHz PIN, the received electrical signals are digitalized by a 64GSample/s digital sampling oscilloscope and then demodulated offline. As seen in Fig. 1(f), the signal demodulation procedures include S/P conversion, CP removal, 256-point FFT operation, equalization, multi-channel de-aggregation and PSK/QAM decoding. In the multi-channel de-aggregation process for each ONU, the required two FFT operation sizes are 32/16 respectively.

B. Upstream Transmission Performance

The measured upstream BER performances of the four channels for each ONU over B2B and the 25km SSMF PONs are illustrated in Fig. 2(a). For the considered SD-FEC threshold at BERs of 2×10^{-2}, the 25km signal transmission-induced upstream transmission performance degradations are <0.6dB for all the considered channels. Fig. 2(b) presents the digital filter characteristic-induced impacts on the upstream transmission performances. In obtaining Fig. 2(b), the upstream transmission distance is 25km and the received optical powers (ROPs) are fixed at -2dBm. For both ONUs, the optimum digital filter length is 16. Fig. 2(b) implies that the proposed transceiver has great relaxation of ONU-embedded digital filter DSP complexity requirement.

Employing the identified optimum digital filter length of 16, the maximum allowable variation range of the optical launch power from a specific ONU [4] is presented in Fig. 2(c) and Fig. 2(d). The ROPs are set to be -2 dBm. It shows that after upstream transmitting over 25km SSMFs, the ONU optical launch power dynamic range of >3.5dB is achievable. To further explore the channel interferences between the considered two ONUs, the upstream BER performances of one ONU with the other ONU's four channels being switched on/off are plotted in Fig. 2(e) and Fig. 2(f), where the fiber transmission distance is 25km and the digital filter lengths are 16. The results indicate that when switching off all the channels of a particular ONU, the BER curves of the other ONU's upstream channels are left-shifted by <1.2dB. This implies that when adopting the identified optimum digital filter length, the channel interferences between different ONUs are negligible.

It is worth mentioning that for practical implementations, the ONUs occupying the low-frequency spectral regions such as ONU1 in this experimental setup can use low-speed transmitters without greatly influencing all other ONUs' upstream transmission performances. While for the OLT, the high-speed receivers are required to simultaneously demodulate the upstream signals from different ONUs.

IV. CONCLUSION

A P2MP flexible transceiver has been proposed and experimentally evaluated in a 55.3Gbit/s@25km upstream IMDD PON. The proposed techniques offer a promising solution for cost-effectively implementing future inherently hub-and-spoke IMDD optical access networks.

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