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***Abstract*— Hybrid OFDM-digital filter multiple access (OFDM-DFMA) PONs exploit software configurable digital shaping filters in ONUs to multiplex multiple gapless OFDM channels at different radio frequencies and utilize a single FFT operation-based pipelined DSP procedure in the OLT to simultaneously de-multiplex/demodulate all OFDM signals from various ONUs without requiring any digital matching filters. In this paper, aggregated raw 30Gbit/s over 25km multipoint-to-point upstream signal transmissions of IMDD OFDM-DFMA PONs are experimentally demonstrated for the first time. Experimental results show that a reduction in ONU-embedded digital filter length from 256 to 16 just decreases the receiver sensitivity by <1dB, which are independent of ONU spectral locations. By utilizing a digital filter length as short as L=16, fibre transmission impairments (channel interference) are shown to give <1dB (<2.5dB) receiver sensitivity degradations. In addition, a >3.5dB (>5.5dB) ONU launch power dynamic range is also achievable for an aggregated upstream transmission raw capacity of 28.12Gbit/s (23.43Gbit/s).**

***Index Terms*— Passive optical networks (PONs), digital filtering, intensity modulation and direct detection (IMDD).**

I. Introduction

Passive optical networks (PONs) based on intensity modulation and direct detection (IMDD) are attractive for implementation of mobile front-hauls/mid-hauls/back-hauls for 5G and beyond networks [1], [2]. However, significant advances in existing IMDD PONs are envisaged as necessary in order to effectively address the ever-increasing 5G and beyond network-associated demands on low latency, ultra-dense connections and high data rates [3]. In addition, to enable IMDD PON-based 5G and beyond networks to offer end-users fast on-demand heterogeneous services, software-defined networking (SDN) [4], [5] from high network layers down to the physical layer is also desirable to flexibly and dynamically reconfigure the networks in a simple, fast and resource-efficient way.

To address the aforementioned technical challenges, digital filter multiple access (DFMA) PONs have been proposed [6]-[8], where multiple gapless channels of arbitrary bandwidth granularity can be dynamically and independently multiplexed/de-multiplexed by transceiver-embedded SDN-controllable digital orthogonal filters without employing additional optical/electrical hardware. However, the digital signal processing (DSP) complexity of the corresponding optical line terminal (OLT) grows proportionally with optical network unit (ONU) count [9], as such for a DFMA PON accommodating a large number of ONUs, the significantly high OLT DSP complexity may become a bottleneck challenge limiting DFMA PON's practical implementation. Therefore, it is greatly beneficial if the OLT DSP complexity is significantly reduced without compromising the salient features associated with the DFMA PONs.

To effectively solve the aforementioned technical challenge associated with DFMA PONs, very recently, a hybrid orthogonal frequency division multiplexing-DFMA (OFDM-DFMA) PON based on IMDD has been proposed [9], [10], where for upstream signal transmissions, by following the DSP procedures similar to the DFMA PONs, each individual ONU employs its embedded software-configurable digital in-phase shaping filters to dynamically locate its OFDM signal at a required sub-wavelength spectral region. Whilst in the OLT, a single fast Fourier transform (FFT) operation-based pipelined DSP procedure is applied to simultaneously de-multiplex and demodulate various OFDM signals from different ONUs without involving any digital matching filters. Compared with the DFMA PONs, such digital matching filter-free pipelined OLT DSP procedure greatly reduces the overall OLT DSP complexity [11]. On the other hand, compared to the DFMA PONs, the hybrid OFDM-DFMA PON also significantly improves the upstream system power budget and upstream performance robustness against component/system impairments, channel interferences and transceiver sample timing offset [9]. Furthermore, the hybrid OFDM-DFMA PON not only has relaxed requirements on ONU-embedded high digital shaping filter DSP complexity for achieving specific transmission performances but also possesses inherent transparency to 4G networks. Apart from the abovementioned salient features, the hybrid OFDM-DFMA PON also has excellent performance robustness to variations in ONU design parameters, this potentially allows a wide diversity of ONUs having different transceiver parameters to transparently and dynamically establish communications connections with the

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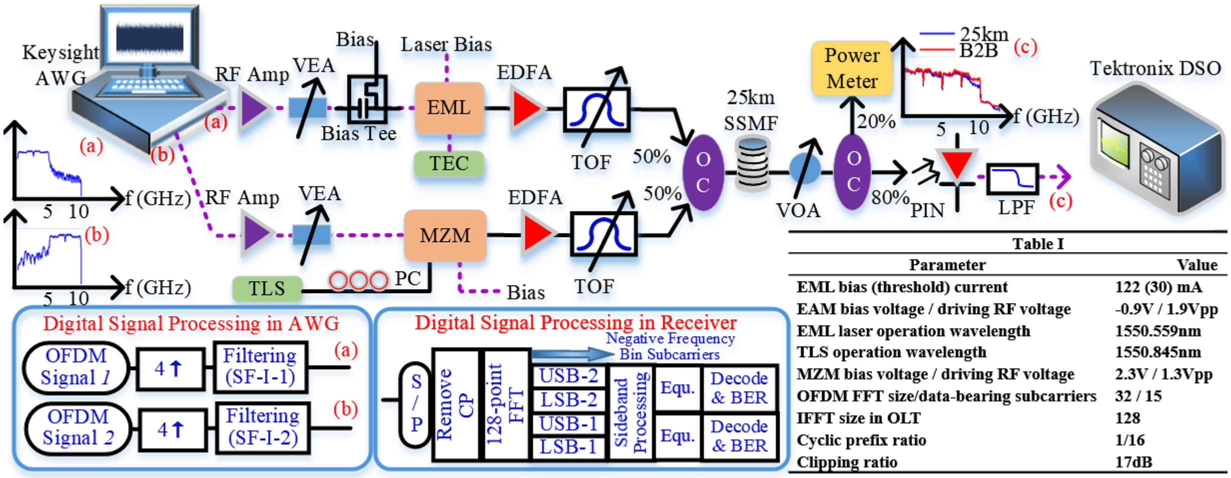

Table I

Parameter	Value
EML bias (threshold) current	122 (30) mA
EAM bias voltage / driving RF voltage	-0.9V / 1.9Vpp
EML laser operation wavelength	1550.559nm
TLS operation wavelength	1550.845nm
MZM bias voltage / driving RF voltage	2.3V / 1.3Vpp
OFDM FFT size/data-bearing subcarriers	32 / 15
IFFT size in OLT	128
Cyclic prefix ratio	1/16
Clipping ratio	17dB

Fig. 1 Experimental setup of the IMDD hybrid OFDM-DFMA PON. SF-I: digital in-phase shaping filter. RF Amp: radio frequency amplifier. VEA/VOA: variable electrical/optical attenuator. TEC: thermo-electric controller. PC: polarization controller. TLS: tunable laser source.

same OLT without requiring additional modifications to ONU/OLT transceiver hardware. Compared with OFDMA PONs, the demonstrated PON has three main advantages [9], including: 1) improved upstream transmission performance and enhanced performance robustness against channel interference; 2) a smaller IFFT size required to produce each individual ONU signal, and 3) no additional DSP required to minimize the intercarrier interference (ICI) effect between different upstream ONU signals. However, our previous investigations of the hybrid OFDM-DFMA PONs have been undertaken utilising numerical simulations only [9]-[11].

To further verify the feasibility of the hybrid OFDM-DFMA PON and rigorously evaluate its practically achievable upstream performance characteristics supported by off-the-shelf optical/electrical devices, in this paper, experimental demonstrations are reported, for the first time, of aggregated raw 30Gbit/s upstream signal transmissions over 25km IMDD hybrid OFDM-DFMA PONs. Our experimental measurements show excellent agreements with our numerical predictions reported in [9]. In addition, this paper also considerably extends the previous work [9] in terms of the following two aspects: a) first experimental demonstrations of the hybrid OFDM-DFMA PON's tolerance to ONU transceiver hardware implementation variations, and b) first experimental explorations of signal transmission capacity-dependent differential ONU launch power dynamic ranges.

II. Upstream Transmission Performance of IMDD Hybrid OFDM-DFMA PONs

A. *Experimental Setup*

The detailed operating principle of the hybrid OFDM-DFMA PON has been presented in [9]. The experimental setup for a two-channel upstream transmission in an IMDD hybrid OFDM-DFMA PON is illustrated in Fig. 1. In the ONU side, a dual-channel arbitrary waveform generator (AWG, Keysight M8195A) with a sampling speed of 30GS/s@8-bit is utilized to produce two independent digitally filtered analogue OFDM signals. The key parameters adopted in producing these two OFDM signals are listed in Table I. For each signal, adaptive subcarrier bit-loading and power-loading are employed on each individual subcarrier and its corresponding subcarrier modulation format is set to either 64-QAM or 128-QAM, as shown in Fig. 2(b). Subsequently, these two digital OFDM signals are respectively 4× up-sampled (4↑) and then digitally filtered by two digital in-phase shaping filters utilising the DSP procedure shown in Fig. 1. In constructing these two adopted digital in-phase shaping filters, a Hilbert-pair approach [6] is employed with a digital filter length of L=16 and an excess of bandwidth factor of α=0. After the digital filtering process, for each OFDM signal, the following three operations are performed, including a digital-domain time delay operation, an extra 1.5×oversampling operation and a signal clipping operation. The digital-domain time delay operation is to synchronise different ONUs. As the hybrid OFDM-DFMA PON is transparent to OFDM-based 4G networks, in practice, full use may be made of synchronisation techniques and protocols that have already been employed in 4G networks. In addition, compared to conventional OFDMA PONs, the hybrid OFDM-DFMA PON has improved performance robustness to the ONU timing offset-induced channel interferences [9]-[11]. Based on the abovementioned experimental settings, each analogue OFDM signal at the AWG output has a signal bandwidth of 5GHz and a signal raw bitrate of 15Gbit/s, thus giving rise to an aggregated upstream signal raw bitrate of 30Gbit/s over a 10GHz spectral region.

To perform optical intensity modulation, a 10GHz electro-absorption modulated laser (EML) and a 50GHz Mach-Zehnder modulator (MZM) are employed. Their optimum bias/driving voltages are listed in Table I. A minimum wavelength space of ~0.28nm between the two ONUs is adopted to mitigate the optical beating interference (OBI) effect [12] in the OLT. Other OBI effect reduction techniques based on cross-channel interference cancellation [11] and self-homodyne coherent detection [12] may also be applicable in the hybrid OFDM-DFMA PONs. Two erbium-doped optical fibre amplifiers (EDFAs) each followed by a 0.8nm bandwidth tunable optical filter (TOF) fix the output optical powers at

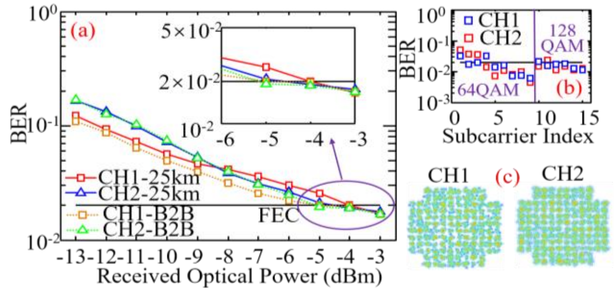

Fig. 2 (a) Back-to-back and 25km SSMF upstream transmission performance, (b) 25km subcarrier BER performance at a received optical power of -3dBm and (c) 128-QAM-encoded subcarrier constellations after 25km SSMF.

6dBm. After a 50:50 passive optical coupler (OC), the fibre launch power is ~5.8dBm.

After transmitting over a 25km standard single mode fibre (SSMF), a 40GHz P type-intrinsic-N type photodetector (PIN) converts the two transmitted upstream optical signals into an electrical signal, followed by an 11GHz electrical low pass filter (LPF) to remove out-of-band noise. The received electrical signal contains two gapless OFDM bands at different radio frequencies as seen in Fig. 1. Subsequently, a digital sampling oscilloscope (DSO) digitizes the received electrical signal at a sampling speed of 25GS/s@8-bit and finally performs off-line signal demodulation process by a Matlab program. The signal demodulation procedure includes signal resampling [8], frame synchronization, serial-to-parallel (S/P) conversion, cyclic prefix (CP) removal, single 128 (32×4) point FFT operation, signal sideband identification, sideband data processing, conventional OFDM subcarrier equalization and QAM decoding. To identify an OFDM signal, the 64 subcarriers in the positive frequency bin are evenly classified into two subcarrier groups. Each group consists of 32 subcarriers and corresponds to an OFDM signal from one ONU. For each identified OFDM signal, its 1st and 17th subcarriers are unable to convey any information, the remaining 15 data-bearing subcarriers (2nd to 16th) in the lower sideband (LSB) and their corresponding subcarriers (18th to 32nd) in the upper sideband (USB) convey identical information [9]. In the subsequent sideband data processing, for each identified OFDM signal, three DSP procedures are successively performed to improve their upstream transmission performance [13]: 1) a conjugate operation applied for the USB subcarriers only, 2) a pilot-aided phase recovery operation conducted for all the subcarriers, and 3) a sum operation between the LSB subcarriers and their USB counterparts. In this experimental setup, the two ONUs share a common clock source embedded in the AWG, while the OLT employs its own embedded clock source.

B. *Upstream 25km SSMF Transmission Performance*

Based on the above experimental setup, the measured upstream bit error rate (BER) performances of the two OFDM signals before and after upstream transmission over the 25km SSMF are plotted in Fig. 2(a). The SNR of the received digital signal after the 25km transmission is ~23.9dB for a received optical power of -3dBm. For the considered 20% overhead soft-decision forward error correction (SD-FEC) threshold at a BER of 2×10^{-2}, the fibre transmission impairment induced upstream transmission performance degradations are almost zero for channel 2 (CH2) and <1dB for channel 1 (CH1). In addition, as seen in Fig. 2(b), due to the adopted adaptive subcarrier bit-loading and power-loading, similar BER distributions among all the OFDM subcarriers are observed between the two ONUs, and Fig. 2(c) illustrates their corresponding constellations of all 128-QAM-encoded subcarriers.

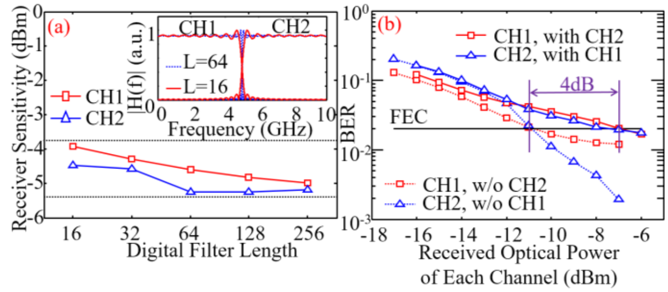

Fig. 3 Impact of (a) ONU-embedded digital in-phase shaping filter characteristic variations and (b) channel interferences on 25km upstream transmission performance.

C. *Impacts of Digital Filter Characteristic Variations*

Based on the aforementioned 25km IMDD hybrid OFDM-DFMA PONs with each ONU having an identical upstream transmission raw bitrate of 15Gbit/s, the impacts of ONU-embedded digital filter length variations on the upstream transmission performances are illustrated in Fig. 3(a). Here the receiver sensitivity, which is defined as the minimum received optical power required to achieve a BER at the FEC limit in the OLT, is plotted as a function of digital filter length for each channel. As the subfigure of Fig. 3(a) shows, a relatively long digital filter length results in relatively flattened digital filter frequency response and reduced digital filter frequency response overlap. While the measured results in Fig. 3(a) show that increasing digital filter length from L=16 to L=256 only leads to <1dB receiver sensitivity improvements, which are independent of ONU spectral locations. As such, the shortest digital filter length of L=16 is thus adopted throughout the paper.

D. *Impacts of Channel Interference Effect*

We experimentally investigate the channel interference effect-induced upstream transmission performance degradations. The BER performance of each channel with the other channel being present/absent in the optical domain is plotted as a function of averaged received optical power for a single channel in Fig. 3(b). For these results, unlike with Fig. 2(a), no alterations are made in the experimental parameters, but in plotting the figure, the BER curves of the two channel upstream transmission cases are left-shifted by 3dB in comparison with those in Fig. 2(a). The results show that when using the shortest digital filter length of L=16, for both channels each transmitting raw 15Gbit/s upstream over 25km SSMF, the OLT receiver sensitivity difference between the abovementioned two cases is ~4dB, of which ~1.5dB is contributed by multi-channel upstream transmission-induced reductions in effective optical signal to noise ratio (OSNR) [6],

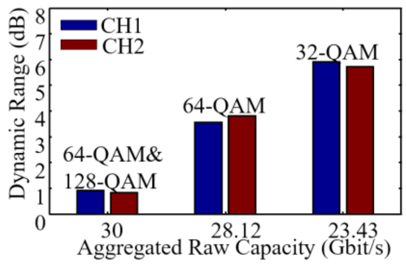

Fig. 4 Differential ONU optical launch power dynamic range versus aggregated upstream transmission raw capacity performances.

and the remaining ~2.5dB is mainly attributed to the channel interference effect. Of the ~2.5dB receiver sensitivity reduction, ~1dB arises due to the digital filter frequency response overlapping-induced power leakages [14].

All the experimental results illustrated in both Fig. 2 and Fig. 3 agree well with our numerical predictions [9], which confirm that the hybrid OFDM-DFMA PONs have excellent upstream performance robustness against transmission system impairments, digital filter characteristic variations and channel interferences.

III. Differential ONU Optical Launch Power Dynamic Range

Based on the experimental setup described in Section II(A), the hybrid OFDM-DFMA PONs' differential ONU optical launch power dynamic range characteristics [9] are examined for various aggregated upstream transmission raw capacities and the results are shown in Fig. 4. In measuring these results, the received optical powers in the OLT are always fixed at -3.5dBm. For each considered case, these two ONUs have identical upstream signal bitrate and their adopted modulation formats are also illustrated in Fig. 4. It can be seen in Fig. 4 that for an aggregated upstream transmission raw capacity of 30Gbit/s, for both ONUs, the differential launch power dynamic ranges of ~0.9dB are observed, which is mainly because of high order modulation format-induced stringent requirements on high OSNR to ensure each ONU's BER performance is below the considered FEC limit. Such a statement can be confirmed by the fact that when the aggregated upstream transmission raw capacity is slightly reduced from 30Gbit/s to 28.12Gbit/s (23.43Gbit/s) by utilizing 64-QAM (32-QAM) modulation format for all OFDM subcarriers in each ONU, the differential launch power dynamic ranges are increased to >3.5dB (>5.5dB). This implies that in the hybrid OFDM-DFMA PONs, a relatively large differential ONU launch power dynamic range is achievable without considerably compromising the aggregated upstream transmission capacity.

It is also worth highlighting that the similar ONU performances in terms of BER and differential ONU launch power dynamic range are achieved using different optical intensity modulators, further supporting the fact that the hybrid OFDM-DFMA PONs have excellent tolerance to ONU transceiver hardware implementation variations.

IV. Conclusions

Aggregated raw 30Gbit/s over 25km upstream transmissions of IMDD hybrid OFDM-DFMA PONs have been experimentally demonstrated for the first time. The experimental results indicate that reducing ONU-embedded digital filter length from L=256 to L=16 only decreases the receiver sensitivity by <1dB, which are independent of ONU spectral locations. Based on a digital filter length as short as L=16, it has been shown that i) fibre transmission impairments (channel interference) only give rise to <1dB (<2.5dB) upstream receiver sensitivity degradations and that ii) raw 28.12Gbit/s (23.43Gbit/s) IMDD hybrid OFDM-DFMA PONs can tolerate >3.5dB (>5.5dB) differential ONU launch power variations.

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