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Experimental Demonstration of Upstream Transmission in Digital Filter Multiple Access PONs with Real-time Reconfigurable ONUs

*Abstract*—Digital filter multiple access (DFMA) passive optical networks (PONs) exploit centralized software defined networking (SDN) controller-managed and transceiver-embedded digital orthogonal filters in individual optical network units (ONUs) to enable end-users to adaptively and dynamically access and share a common fiber transmission medium. DFMA PONs have the potential of not only equipping NG-PONs with sufficient network operation flexibility, adaptability, elasticity and reconfigurability, but also providing highly desirable backwards compatibility with current PON standards. In this paper, for the first time, multipoint-to-point upstream signal transmission in intensity-modulation and direct-detection (IMDD) DFMA PONs is experimentally demonstrated using two real-time, reconfigurable, optical orthogonal frequency division multiplexing (OOFDM)-modulated ONUs and an offline optical line terminal (OLT). Experimental demonstrations show that each ONU achieves similar upstream bit error rate (BER) performance, excellent tolerance to inter-ONU sample timing offset and a relatively large ONU launch power variation range.

*Index Terms*—Digital filtering; Digital signal processing (DSP); Passive optical networks (PONs); Software-defined networking (SDN); Orthogonal frequency division multiplexing (OFDM).

1. INTRODUCTION

The unprecedented ever-increasing growth of end-users’ data traffic associated with a widely diversified range of bandwidth-hungry Internet applications and services has motivated extensive research and development interest in next-generation passive optical networks (NG-PONs) [1]. Consequently, recent years have seen attention moving away from the traditional time domain multiplexed PON technologies [2] to PON technologies employing signal multiplexing in the wavelength domain [3], hybrid time/wavelength domains [4] and frequency domains [5-7]. Moreover, as end-users’ broadband data traffic patterns

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become increasingly dynamic, this causes great challenges for efficient bandwidth provision. It is, therefore, essential to equip NG-PONs with software defined networking (SDN)-based operation capability with centralized virtualization and abstraction [8-10] to offer highly desirable network operation functionalities including reconfigurability, flexibility, adaptability, backward compatibility and elasticity. The abstraction facilitates the formation of a technology-agnostic platform which provides a consolidated view of diversified optical technologies and devices, whereas the virtualization facilitates the partitioning of the physical network infrastructure into multiple independent networks each tailored to a specific application or service requirement. Furthermore, to further improve the network bandwidth utilization efficiency, network operation functionality, power consumption efficiency and cost effectiveness, the heterogeneous amalgamation of traditional optical access networks, metropolitan area networks and 4G/5G mobile front-haul/back-haul networks [11-13] into a seamlessly integrated flexible cloud access network (CAN) is also highly preferred for designing and implementing sustainable “future-proof” optical access networks.

 To address the aforementioned technical challenges, we have recently proposed and theoretically investigated a novel multiple access PON technique, designated as digital filter multiple access (DFMA) PON [14], in which use is made of centralized SDN controller-managed and transceiver-embedded digital orthogonal filters to enable various optical network units (ONUs) to adaptively and dynamically access and share a common fiber transmission medium. It has been shown [14] that the proposed DFMA PONs have a number of salient advantages as listed below:

* Significantly expanded and improved network operation functionalities and reconfigurability in both the electrical and optical domains, along with considerably extended SDN network virtualization and abstraction capabilities to the physical layer;
* Excellent network operation transparency to underlying signal modulation/detection technique, signal bandwidth, wavelength grid, multiple access technique and network topology. This feature offers a solid platform for equipping NG-PONs with sufficient network flexibility, adaptability and elasticity. The feature also provides highly desirable backwards compatibility with all existing PONs. In addition, this feature also greatly simplifies the development of universal ONU transceivers in a cost effective manner;



Fig. 1. Proposed DFMA PON architecture supporting the SDN paradigm. *(Note: For ease of reference this figure is recreated from [14]).*

* The ability to realise the aforementioned cloud access networks when utilising our recently proposed flexible reconfigurable optical add/drop multiplexers (ROADMs) [15] capable of performing DFMA-based channel add/drop functions;
* Improved physical layer data security as dynamic digital filter parameters must be known for receiving data;
* Network implementation using a “pay as you grow” operation model, as new DFMA channels can be added on-line as required.

To rigorously verify theoretical predictions presented in [14] and further explore major DFMA PON aspects related to their practical implementation, in this paper, we report, for the first time, experimental demonstrations of multipoint-to-point upstream optical orthogonal frequency division multiplexed (OOFDM) signal transmission in intensity-modulation and direct-detection (IMDD)-based DFMA PONs incorporating real-time digital orthogonal filtering-enabled reconfigurable ONUs. Given the fact that the DFMA PON downstream transmission performance is very similar to that corresponding to a digital orthogonal filtering-enabled point-to-point PON system [7,16], the work reported here focuses on the experimental demonstration of the more challenging upstream DFMA PON transmission, where two orthogonal channels occupying the same signal spectral region are optically combined passively in an optical coupler at the remote note. In addition, to investigate the DFMA PON upstream performance characteristics, comprehensive experimental investigations are also undertaken of ONU reconfigurability-induced power penalties, and ONU bit error rate (BER) performance sensitivity to both sample timing offset (STO) between different upstream ONUs as well as the ONU differential launch power variation range. Such first experimental demonstration of multipoint-to-point DFMA PON upstream transmission is highly significant as it not only experimentally confirms the feasibility of the previously proposed DFMA concept, but also offers a unique opportunity of critically validating the DFMA PON technique. Also importantly, the results presented in this paper provide insights into the DFMA PON aspects associated with its practical implementation.

As already stated above, the DFMA PON is inherently transparent to signal modulation format. In this paper, special attention is focused on OOFDM, as OOFDM is regarded as a promising candidate for NG-PONs because of its high spectral efficiency and digital signal processing (DSP) richness. Similar to conventional OOFDM, fast OOFDM (FOOFDM) [17] is also capable of achieving the Nyquist rate utilizing only half of the conventional OOFDM subcarrier spacing, thus potentially further improving spectral efficiency. However, FOOFDM is just suitable for signal modulation formats with one-dimension constellation diagrams only. On the other hand, four-level pulse-amplitude modulation (PAM-4) [18] is currently considered for high-speed short-reach optical access application scenarios because of its low implementation complexity. However, PAM-4 has limited support for network operation features such as adaptability to channel spectral characteristics, compensation for component/system/network imperfections, and dynamically variable transmission capacity versus reach performance.



Fig. 2. (a) Upstream DFMA PON experimental system setup; (b) Major DSP functions in both the ONUs and the OLT. The insets are the electrical spectra of the ONU and OLT signals. DFB: distributed feedback laser, EML: electro-absorption modulated laser, EDFA: Erbium-doped fiber amplifiers, OBPF: optical band-pass filter, VOA: variable optical attenuator, OC: optical coupler, SSMF: standard single-mode fiber, PIN+TIA: photodetector with integrated transimpedance amplifier.

1. DFMA PON Operating Principle and Experimental System Setup
2. Operating principle

 Detailed descriptions of the DFMA PON operating principle have already been presented in [14], thus only the basic principles are outlined below. As illustrated in Fig. 1, a DFMA PON utilises digital orthogonal filtering to multiplex/demultiplex various downstream signals. For the upstream operation, each ONU first digitally generates data encoded using an arbitrary signal modulation format, the produced digital data is then M× up-sampled by inserting M-1 zeroes between two successive samples of the original data. The up-sampled data sequence is then digitally filtered with a dynamically reconfigurable digital shaping filter (SF). The digitally filtered data sequence is converted to an analogue electrical signal via a digital-to-analogue converter (DAC). Finally, electrical-to-optical (E-O) conversion is performed by an optical intensity modulator (IM). Optical signals from various ONUs, each generated with a different digital shaping filter, are all passively combined by an optical coupler (OC) in the remote node, and the combined optical signal propagates through the fiber transmission link to the optical line terminal (OLT).

 In the OLT receiver, the optical signal is detected by a square-law photodetector (PD) to convert the signal from the optical domain to the electrical domain. After that, the electrical signal is amplified, analogue low-pass filtered and subsequently digitized by an analogue-to-digital converter (ADC). Next, the data stream is digitally filtered by a matching filter (MF) suitably configured with the appropriate coefficients corresponding to the specific ONU signal to be demultiplexed. The filtered signal is then down-sampled by selecting every M-th sample with the optimum phase. Data from the specific ONU is finally recovered by allowing for any underlying multiple-access schemes (if any) and also by applying suitable demodulation for the modulation format employed by the associated ONU.

 Based on the currently active services and dynamic network traffic characteristics, the centralized SDN controller negotiates with the OLT and ONU-embedded DSP controllers, via extended OpenFlow [19], to determine all sets of digital filter coefficients to perform the shaping (matching) filtering process required by each individual ONU (the OLT). This leads to the flexible creation of software-reconfigurable elastic connections at the physical layer. In addition, the OLT-embedded DSP controller oversees the DFMA channel allocation, and takes full responsibility for maintaining the orthogonality between all channels employed in the DFMA PON.

In the DFMA PON, the Hilbert-pair approach [7] is employed to implement the necessary digital orthogonal filters. The *i*-th Hilbert-pair filters, *hi(t)*, have impulse responses of:

 (1)

where the spectrally overlapped in-phase and quadrature-phase Hilbert-pair filter components are designated by the superscripts “I” and “Q”, respectively, *fci* is the *i*-th Hilbert-pair filter central frequency, and *p(t)* is the baseband pulse with a square-root raised-cosine form [20] expressed as:

 (2)

where *Ts* is the sampling period preceding the up-sampling and the *α* parameter governs the excess of bandwidth of *p(t)* in the frequency domain. Each of the orthogonal filter components can be used to transmit an independent signal, for example, a signal from each individual ONU.

The OLT-embedded digital filters are matched versions of the corresponding ONU shaping filters, thus the impulse responses, *gi(t)*, are:

TABLE I

Transceiver and System Parameters

|  |  |  |
| --- | --- | --- |
| Parameter | Value | Unit |
| Total number of IFFT/FFT pointsData-carrying subcarriersAdaptive subcarrier modulation formats Number of filter tapsDAC sample rateDAC resolutionDSO sample(resample) rateOFDM symbol rateSamples per OFDM symbol*α*Cyclic prefix*α*Total samples per OFDM symbol*α*Signal clipping ratioRaw signal line rate per ONUEML laser operating wavelength3dB EML modulation bandwidthEML bias current EAM bias voltageEML driving voltageDFB laser operating wavelength3dB DFB modulation bandwidthDFB laser bias currentDFB laser driving voltagePIN detector bandwidthPIN detector sensitivity*β* | 326 at highest frequencies16-QAM, 32-QAM322825(2)2532 samples (16ns)8 samples (4ns)40 samples (20ns)130.751550.94810125-0.71.561550.745104229512-19 | ////GS/sbitsGS/sMHz///dBGb/snmGHzmAVVppnmGHzmAmVppGHzdBm |

 (3)

with

 (4)

where the superscripts A and B each indicate I or Q, and *t0* is the total time delay induced by the digital filters. To support N independent ONU signals, the up-sampling factor, M, must satisfy M ≥ N [7]. This implies that, when each individual ONU has a fixed signal transmission capacity, the minimum required electrical bandwidth for each ONU increases with increasing ONU count in the DFMA PON. Furthermore, when the DAC and the ADC operate at identical sampling speeds of , the i-th Hilbert-pair has a central frequency, *fci*, given by:

 (5)

The central frequency of each Hilbert-pair can be dynamically chosen according to the traffic requirement and/or digital filter availability to enable efficient network bandwidth resource usage with a reduced traffic blocking probability.

1. Experimental System Setup

Fig. 2 illustrates the considered DFMA PON upstream experimental system setup, which consists of two independent real-time ONUs feeding a 3dB optical coupler, a 26.4km SSMF IMDD transmission link and an offline OLT with a PIN+TIA. According to our numerical simulation results [14], for a specific ONU, the cross-talk effect between two ONUs occupying the same spectral region has a significant impact on the maximum achievable upstream performance of the ONUs, whilst the cross-talk effect between all other ONUs occupying different spectral regions is almost negligible. For simplicity but without loss of generality, in this paper, two ONUs named ONU1 and ONU2 are considered, each utilizing an entire I or Q channel constructed by a single Hilbert-pair filter of the same central frequency. ONU1 is composed of an FPGA- and 8bit@2GS/s DAC-based real-time software reconfigurable OOFDM transmitter [16], where a 10GHz directly modulated distributed feedback (DFB) laser (DML) is employed to perform the E-O conversion. An EDFA followed by an optical filter is also utilized to set the optical launch power at a desired level. The architecture of ONU2 is almost identical to ONU1, except that in ONU2 a 10GHz electro-absorption modulated laser (EML) is employed as an intensity modulator (IM) and an electrical RF delay line is also introduced to alter the inter-ONU STO. The employment of different intensity modulators in various ONUs enables rigorous evaluations of the DFMA PON upstream performance robustness to different intensity modulator types.

*α* Before up-sampling / after down-sampling

 *β* Equivalent to 10 Gb/s NRZ data (PRBS 231-1) at a BER of 1×10−9

As seen in Fig. 2 (a) and (b), in each individual real-time ONU transmitter, after generating a pseudo random binary sequence (PRBS)-based OFDM signal in the corresponding FPGA, the digital signal is first 2× up-sampled by introducing a zero-valued sample between two consecutive original samples. The up-sampled digital signal consisting of 16 parallel samples is then filtered by a bank of 16 parallel 32-tap finite impulse response (FIR) digital shaping filters to generate an I signal for ONU1 or a Q signal for ONU2. It should be noted that the I and Q signals can also be simultaneously assigned to a single ONU with suitably designed DSP [7,16]. Furthermore, a single I or Q signal can also be shared by two or more ONUs using a multiple access method such as OFDMA [6].

To implement the embedded digital orthogonal filters in the real-time transmitters, two Hilbert-pair-based shaping filters are employed [16] which have discrete impulse responses of:

 (6)

 (7)

where k = 0, 1, 2, …, 31, where the maximum k value is determined by the total number of taps. *Tp* is the sampling period after up-sampling and *g(k)* is the baseband pulse with a square-root raised-cosine form:

 (8)

where the excess of bandwidth determining the minimum signal bandwidth of 1/(2*Ts* ) is controlled by the α parameter, which can vary over a range from 0 to 1. Here other key filter parameters employed in *s1(k)* and *s2(k)* are: the excess of bandwidth α=0, the filter pair central frequency *fc1* = 500MHz and the sampling time interval *Tp* = 500ps. After having passed through a DAC, a RF gain stage, and combined with an optimized bias current, the digitally filtered OFDM signal directly drives the corresponding optical intensity modulator in each ONU. The inter-ONU STO between these two ONUs is optimized using the RF delay line included in ONU2. The optical launch power from each ONU is fixed at 4dBm. These two upstream OOFDM signals occupying the same spectral region (0-1GHz) but different locations in the digital filter space, are subsequently passively combined in the optical domain with a 3dB optical coupler, and the combined optical signals propagate to the OLT through a 26.4km SSMF link. Both the 4dBm optical launch power from each ONU and the 26.4km SSMF length are chosen to represent typical PON scenarios.

 In the OLT, a variable optical attenuator is utilized to vary the received optical signal power before injecting into a 12.4GHz PIN with a receiver sensitivity of -19dBm. After passing through a 2GHz electrical low-pass filter, the converted signal is sampled at 25GS/s by a real-time digital sampling oscilloscope (DSO) and subsequently processed off-line using MatLab for recovering data from either ONU1 or ONU2. The major OLT receiver DSP functions include: down-sampling to 2GS/s, selecting the optimum STO, filtering with a digital matching filter selected according to the ONU data to be recovered, 2× down-sampling, OFDM symbol synchronisation, detection of pilot subcarriers and channel estimation/equalization, as well as other DSP functions that are inverse to the transmitter’s DSP counterparts. The selected digital matching filter frequency response satisfies:

 (9)

 (10)

with

 (11)

where *k0* is to the overall discrete time delay due to both filters. The optimum IM operating conditions adopted are: a DFB bias current of 42mA, an EML laser bias current of 125mA and an EML bias voltage of -0.7V, as well as a driving signal level of 295mVpp (1.56Vpp) for the DFB (EML). The wavelength of the DML is fixed at 1550.745 nm, whilst the wavelength of the EML is kept at 1550.948 nm. According to our experimental measurements [6], such a wavelength spacing between different ONUs is sufficiently large to completely eliminate the optical beat interference (OBI) effect associated with direct detection of the combined upstream signals in the OLT.

Due to finite tap count-induced digital filter frequency response ripples and channel frequency response roll-off-induced cross-talk between two spectrally overlapped DFMA channels [14,16], only the 6 highest frequency subcarriers (out of 15) are used for each ONU to avoid the occurrence of excessive errors on the lower frequency subcarriers. It is, however, expected that all 15 subcarriers could be used by applying our recently proposed cross-channel interference cancellation (CCIC) technique [21]. The key transceiver and system parameters are summarized in Table I. Based on Table I and taking into account the adopted signal modulation formats, the raw upstream signal transmission capacity per ONU is ~0.75Gb/s, and the raw aggregated upstream DFMA PON transmission capacity is thus ~1.5Gb/s. The net upstream signal transmission capacity per ONU is ~0.6Gb/s and the net aggregated upstream DFMA PON transmission capacity is ~1.2Gb/s because of the following two reasons: a) a pilot subcarrier insertion approach reported in [22] is used, which requires negligible signal bandwidth, and b) a 25% OFDM cyclic prefix is considered, as presented in Table I. Here it is also worth addressing that accurate synchronisation between two orthogonal upstream ONU signals occupying the same spectral region in a DFMA PON is vital for maximizing the ONU upstream transmission performance. In contrast, no synchronisation is required between ONU signals occupying different spectral regions. According to our numerical simulations [14], no spectral guardband is necessary between two adjacent spectral regions. By making use of our previously published synchronisation approach [6,23], and considering the fact that the received signal at the DSO is sampled at 25GS/s, the following synchronisation approach is adopted here, which is experimentally proven to be very effective at achieving accurate synchronisation:

* In the initial phase of establishing an upstream DFMA PON system, ONU1 is switched on and ONU2 is switched off. In the OLT, after the ADC function within the DSO, the digitized signal is first resampled to 26GS/s, and then down-sampled to 2GS/s by selecting every 13th sample, the signal is subsequently passed through a corresponding matching filter, down-sampled by a factor of 2 and finally OFDM demodulated for BER calculations.
* A comprehensive sample sweep (at 26GS/s) across two consecutive sample intervals (at 2GS/s) with a total sweep time interval of 1ns is conducted. By comparing the BER performances for different samples, the optimum sample can be easily identified for ONU1.
* Having synchronised ONU1, ONU2 is then switched on. After applying the relevant procedures mentioned above, the inter-ONU STO between these two ONUs is then optimized using the RF delay line included in ONU2. The RF delay is adjusted to minimise the BER on both channels.

It should also be addressed that, to easily differentiate the upstream signals emerging from ONU1 and ONU2, different signal modulation formats are implemented in ONU1 where 32-QAM is taken only on the 15th subcarrier and 16-QAM is taken on all other data-carrying subcarriers. Such signal modulation format manipulation is not necessary for practical application scenarios. On the other hand, all the data-carrying subcarriers in ONU2 are encoded using 16-QAM.

1. Experimental Results

Having outlined the DFMA PON operating principle in Section 2 and described the experimental upstream system setup in Section 3, this section is dedicated to extensively exploring key upstream DFMA PON performance properties, which include ONU BER performance, ONU reconfigurability-induced power penalties, and performance tolerance to inter-ONU STO as well as differential ONU launch power variation range. Understanding these issues is of great importance for system design.



Fig. 3. (a) BER performance of aggregated 1.5Gb/s OOFDM upstream transmission over 26.4 km SSMF IMDD DFMA PON systems; (b) Example of received constellations of the 15th subcarriers for both ONU1 and ONU2.

* 1. Upstream DFMA PON performance

The upstream ONU BER performances versus received optical power (ROP) for optical back-to-back (BTB) and 26.4km SSMF transmission are both plotted in Fig. 3(a), which shows almost identical BER performances for both ONUs, as theoretically predicted in [14]. At the adopted FEC limit of 4×10-3, for both ONUs, negligible power penalties are also observed, compared to the corresponding optical back-to-back cases. All these results mentioned above indicate that the DFMA PON upstream performance exhibits excellent robustness to different IM types.

To explore the ONU reconfigurability-induced optical power penalty, Fig. 3(a) presents the BER performance of each ONU with the other ONU deactivated. Fig.3(a) emulates the worst-case reconfiguration scenario where one ONU’s IM driving current is turned off and its corresponding optimum IM bias current is still active. Fig. 3(a) shows that, at the assumed FEC limit, the DSP-enabled ONU reconfigurability-induced optical power penalty is 1.8dB (2.3dB) for ONU1 (ONU2). It is also expected that the power penalties for the worst-case scenarios can be considerably reduced when the reconfigurability takes place between different ONUs utilizing digital filters at different central frequencies. Moreover, in comparison with the case where two ONUs are activated simultaneously, the existence of a single active ONU produces a sharper BER developing curve, as seen in Fig. 3(a). This is very similar to our previous experimental results measured in a point-to-point system [16]. This confirms the theoretical predictions [14] that the cross-talk effect between two spectrally overlapped ONUs is a major physical mechanism underpinning the minimum attainable BERs of the DFMA PON. This suggests that the optical power penalty is independent of the ONU count in the DFMA PON. Here it is also worth pointing out that the cross-talk effect can be substantially diminished by employing the CCIC technique [21]. For two active ONUs and a ROP of -9dBm, the representative equalized constellations of 15th subcarriers are shown in Fig. 3(b).

* 1. Tolerance to inter-ONU STO

As mentioned previously, achieving suitable timing synchronisation between ONUs occupying the same signal spectral region is essential for the DFMA PON. Thus, the upstream ONU BERs as a function of inter-ONU STO are plotted in Fig. 4, where STO = 0 represents an ideal timing relationship between these two involved ONUs. In obtaining Fig. 4 the inter-ONU STO is varied by adjusting the electrical RF delay line in ONU2 with ONU1 being kept at its optimum synchronised status. In measuring Fig.4, each ONU optical launch power is fixed at 4dBm, and the total ROP at the OLT remains at -9dBm. Physically speaking, when the STO varies within the sample period of 500ps, an unwanted signal power leakage between the two spectrally overlapped ONUs occurs, which grows with increasing STO. As such, it is shown in Fig. 4 that to maintain upstream ONU BERs below the adopted FEC limit, both ONUs can tolerate an inter-ONU STO as large as 0.22ns, which is approximately 44% of the sample interval of 500ps. Modern clock timing circuits are capable of easily achieving the timing stability within such a range.



Fig. 4. ONU BER performance tolerance to inter-ONU STO

It is also interesting to note in Fig.4 that ONU2 is more sensitive to STO than ONU1. This is due to the fact that, the status of STO = 0 for ONU1 always maintains the optimum timing relationship between its associated shaping and matching filters, and so it only suffers power leakage from ONU2 due to the inter-ONU STO induced degradation in orthogonality. Whereas, the performance of ONU2 degrades as its STO deviates further from the ideal state. The recovered signal from ONU2 will not suffer increased leakage from ONU1 as timings and delays related to ONU1 are unchanged. Fig.4 shows that the STO variation of ONU2 has a greater impact than the associated increased leakage on ONU1. Therefore, as shown in Fig.4, the ONU which experiences the timing delay exhibits higher inter-ONU STO sensitivity than the ONU where timing delay was unchanged. From the above analysis, it is easy to appreciate that the DFMA PON’s tolerance to inter-ONU STO can be considerably improved when further digital filter optimizations are made. It should also be pointed out, in particular, that the aforementioned STO-induced power leakages are negligible between ONUs occupying different signal spectral regions.

* 1. ONU launch power variation range

For a specific ONU, the launch power variation range is defined as the maximum allowable variation in its optical launch power, for a given ROP at the OLT, which maintains the BERs of all simultaneously transmitting ONUs below the adopted FEC limit. To examine the achievable ONU launch power variation range for the considered DFMA PON, Fig. 5 is presented, where the BER performances of all upstream signals are plotted against optical launch power of each individual ONU. In obtaining Fig. 5, an EDFA is used to vary the optical launch power emerging from the variable-power ONU, whilst the optical launch power from the fixed-power ONU is always kept at a constant value of 4dBm. The ROP at the OLT remains at -9dBm.



Fig. 5. ONU launch power variation range for the DFMA PON. (a) The optical launch power from the DML-based ONU1 varies and the optical launch power from the EML-based ONU2 is fixed at 4dBm. (b) The optical launch power from the DML-based ONU1 is fixed at 4dBm and the optical launch power from the EML-based ONU2 varies.

It is observed in Fig. 5 that, for a fixed total ROP of -9dBm in the OLT, increasing the optical launch power from the variable-power ONU improves its own BER performance and simultaneously degrades the BER performance of the fixed-power ONU. This mainly results from the variation in the effective optical signal-to-noise ratio (OSNR) of the corresponding upstream optical signals. It can be easily seen in Fig. 5(a) and Fig. 5(b) that the ONU launch power variation ranges are approximately 3.8dB for ONU1 and 3.0dB for ONU2. The observed launch power variation ranges are mainly attributed to three major physical mechanisms: the cross-talk effect induced by the imperfect ONU filter orthogonality, the non-ideal channel frequency response, and the relatively low extinction ratios (<0.2dB) of the intensity modulated optical signals [24]. Very similar launch power variation ranges have also been experimentally observed in OOFDMA PONs [6]. For a practical DFMA PON, its upper limit of the launch power variation range is determined by the minimum OSNR allowed by the fixed-power ONU, whilst its lower limit of the launch power variation range is determined by the minimum OSNR allowed by the variable-power ONU. In addition, it is also seen in Fig.5 that the minimum achievable BERs for ONU2 are lower than those for ONU1 for all the cases, this is because the EML employed in ONU2 has better intensity modulation performance characteristics compared to the DML employed in ONU1.

1. Conclusions

For the first time, upstream IMDD DFMA PON transmission has been experimentally demonstrated, by making use of two real-time reconfigurable OOFDM-modulated ONUs and an offline OLT. Experimental results have shown that the employed ONUs have similar upstream BER performances, negligible power penalties, excellent tolerance to inter-ONU STO, and large ONU launch power variation ranges. The proof-of-concept experimental work implies that the DFMA technique has great potential for implementing future SDN-based reconfigurable cloud access networks.

To further improve the DFMA PON upstream performance, experimental investigations utilising our recently proposed CCIC technique [21] are currently undertaken in our research laboratory, and relevant research results will be reported elsewhere in due course.

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