Layered PAM-DMT for Next Generation Passive Optical Networks

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ABSTRACT

Layered pulse amplitude modulation with discrete multitone (PAM-DMT) is proposed to improve the system spectral efficiency of existing passive optical networks (PONs) by modulating both the real and imaginary parts of the subcarriers through different layers. Signals from different layers are then combined for simultaneous transmission. At the receiver, an iterative receiver is used to remove the clipping distortion introduced by previous layers. Throughout simulations, we demonstrate enhancement in the receiver sensitivity and the PON reach compared to conventional PAM-DMT when compared at same spectral efficiency. Moreover, the spectral efficiency can be improved by approximately 100% using ($\log_2 N$ - 1) layers compared to conventional PAM-DMT systems, where N is the length of the PAM-DMT sequence.

Keywords: layered PAM-DMT, OFDM, PON, spectral efficiency.

1. INTRODUCTION

Passive optical networks (PONs) have been widely recognized as a promising solution for future gigabit optical access networks to meet the continuously increasing bandwidth demand. Orthogonal frequency-division multiple-access (OFDMA) has attracted much research interest for next generation PONs (NG-PONs) due to its resilience to inter-symbol interference (ISI). In addition, it simplifies the receiver design as equalization can be performed with single tap equalizers in frequency domain [1], [2].

NG-PONs must offer low cost and energy consumption while providing large capacity. For that purpose optical access networks should be coupled with intensity modulation/direct detection (IM/DD) systems. In IM/DD systems, the transmitted signal has to be real-valued and non-negative. To generate real OFDM signals, Hermitian symmetry is often imposed on the OFDM subcarriers [3], [4]. To generate unipolar time-domain signals, there are two commonly used techniques; DC-biased and clipping based solutions [3], [4]. In DC-biased optical OFDM (DCO-OFDM), the signal is forced to be non-negative by adding a DC bias at the expense of reducing the power efficiency. On the other hand, clipping based solutions as in asymmetrically clipped optical OFDM (ACO-OFDM) and pulse-amplitude-modulated discrete multitone (PAM-DMT), generate asymmetrical signals. In ACO-OFDM, only the odd subcarriers are modulated, whereas in PAM-DMT only the imaginary part of subcarriers is modulated leading to degradation in the spectral efficiency. A spectrally efficient layered ACO-OFDM scheme has been recently proposed in [5] for IM/DD optical wireless transmission, where the subcarriers are modulated through different layers using ACO-OFDM. These layers utilize different sizes of inverse fast Fourier transform (IFFT), then ACO-OFDM signals are combined for simultaneous transmission. In this way, both even and odd subcarriers can be used for data transmission.

In this paper, we introduce layered PAM-DMT to double the spectral efficiency of NG-PONs compared to conventional systems by modulating both the real and imaginary parts of the subcarrier. This is performed over different layers at the transmitter side with different IFFT sizes. An iterative receiver is proposed to remove the clipping distortion from the upper layers that falls on the real part of the subcarriers. We show that when using 2- and 3-layers, the spectral efficiency could be improved by 50% and 75% respectively. Improvement in the required receiver sensitivity and the PON reach is also reported for the proposed layered PAM-DMT and compared to conventional system for same spectral efficiency.

2. PROPOSED LAYERED PAM-DMT SYSTEM

For conventional PAM-DMT [6], Hermitian symmetry has to be satisfied while setting to zero the real part of the subcarrier and only modulating the imaginary part with PAM symbols. If we denote the frequency domain signal by X_k as in (1), the time domain signal x_n will have anti-symmetry property as in (2), so that the signal can be clipped without loss of information as illustrated in Fig. 1(c).

$$X_k = \left[0, jX_1, jX_2, jX_3, \ldots\ldots, jX_{\frac{N}{2}-1}, 0, -jX_{\frac{N}{2}-1}, \ldots\ldots, -jX_3, -jX_2, -jX_1\right] \tag{1}$$

$$x_n = -x_{N-n} \qquad for\ 0 < n < \frac{N}{2} \tag{2}$$

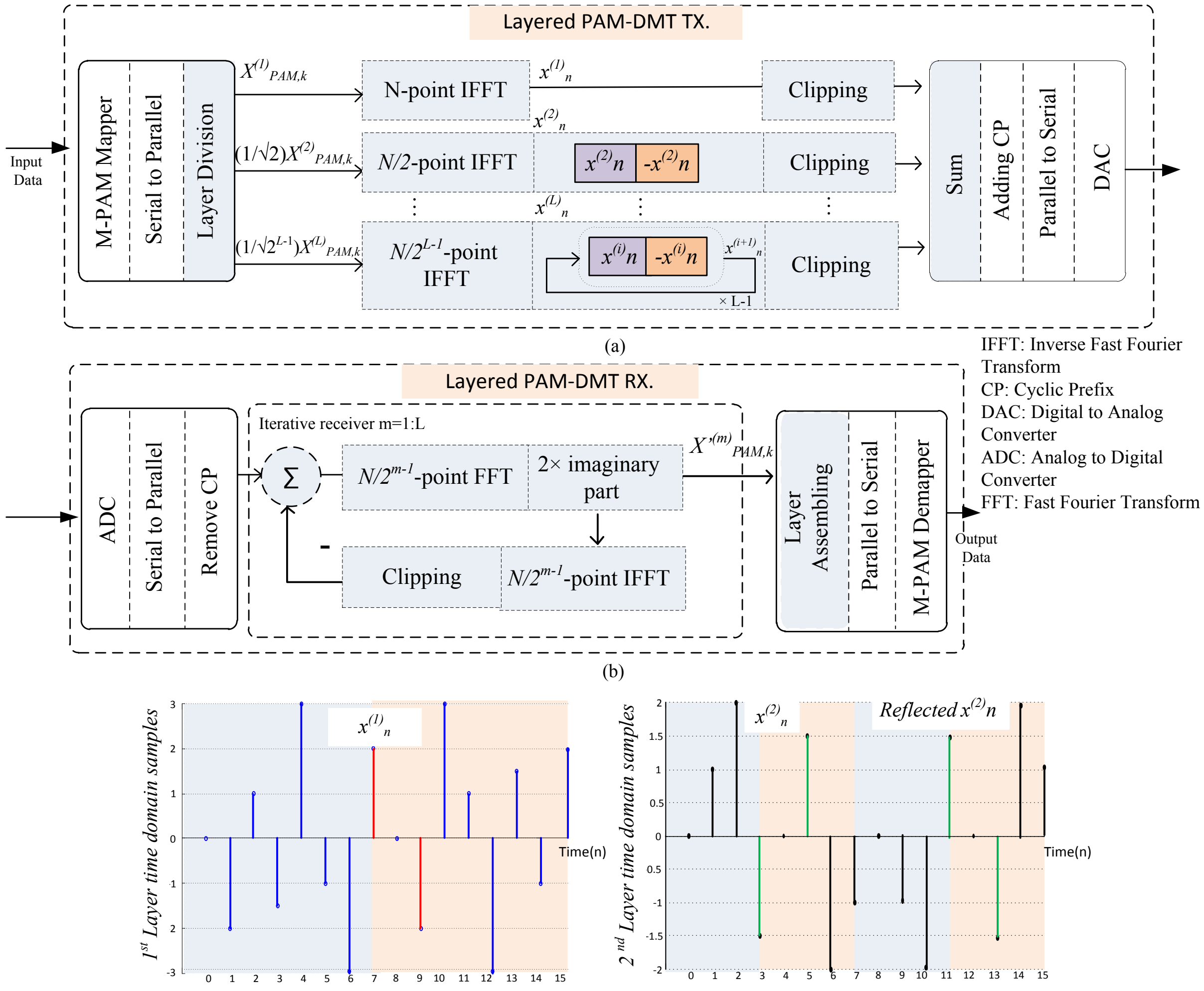


Figure 1. Proposed L- Layered PAM-DMT: (a) transmitter , (b) iterative receiver, (c) first layer time domain samples, and (d) second layer time domain samples.

For a 2-layer PAM-DMT system, if we consider modulating the real part of the subcarriers the output will have symmetry property and by modulating the odd subcarriers as in (3) we ensure that each half of the output sequence will have anti-symmetry property as shown in Fig. 1(d), hence clipping can be performed. In addition, both the signal and clipping distortion of second layer fall on the real part of the subcarriers and do not affect the imaginary part of the subcarriers in the first layer. It can be seen that x_n can be obtained with $N/2$-point IFFT (3). Also it can be proved that the input sequence to $N/2$-point IFFT is purely imaginary sequence as given in (4), where $X'_{\text{real}}(m)$ is the same odd sequence of $X_{\text{real}}(k)$.

$$x_n = \frac{1}{\sqrt{N}}\sum_{k=0}^{\frac{N}{2}-1} X_{real}(2k+1)\, e^{\frac{j2\pi n(2k+1)}{N}} = \frac{1}{\sqrt{2}}.\frac{1}{\sqrt{N/2}}\sum_{k=0}^{\frac{N}{2}-1} X_{real}(2k+1)\, e^{\frac{j2\pi nk}{N/2}}\, e^{\frac{j2\pi n}{N}} \tag{3}$$

$$Y_k = \frac{1}{\sqrt{N/2}}\sum_{n=0}^{\frac{N}{2}-1} x_n e^{\frac{-j2\pi nk}{N/2}} = \frac{j}{\sqrt{2}}\frac{1}{N/2}\sum_{m=0}^{\frac{N}{2}-1} X'_{real}(m)\cot\left(\frac{\pi(2m+1-2k)}{N}\right) \tag{4}$$

Similar to previous analysis, we can show that the real part of the rest subcarriers can be modulated at the transmitter using L- layers PAM- DMT. The IFFT size of layer-l will be $N/2^{l-1}$, and the output samples of layer-l $x_n^{(l)}$ will be reflected and concatenated with $x_n^{(l)}$ due to the periodicity of x_n. The process of reflection and concatenation will be repeated l-1 times on the resulted samples to complete the rest of N-samples. Afterwards, the time domain of PAM-DMT signals from different layers are combined and simultaneously transmitted as shown in Fig. 1(a). The number of transmitted PAM symbols using L-layers PAM-DMT is $(1 - 1/2^L)N$, which is $(2 - 1/2^{L-1})$ times the conventional PAM-DMT, also the spectral efficiency of the system can be approximately twice the conventional one when using the maximum possible number of layers ($\log_2 N$ - 1). An iterative receiver

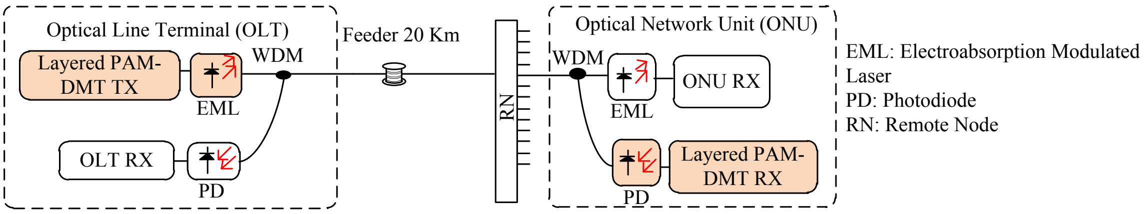
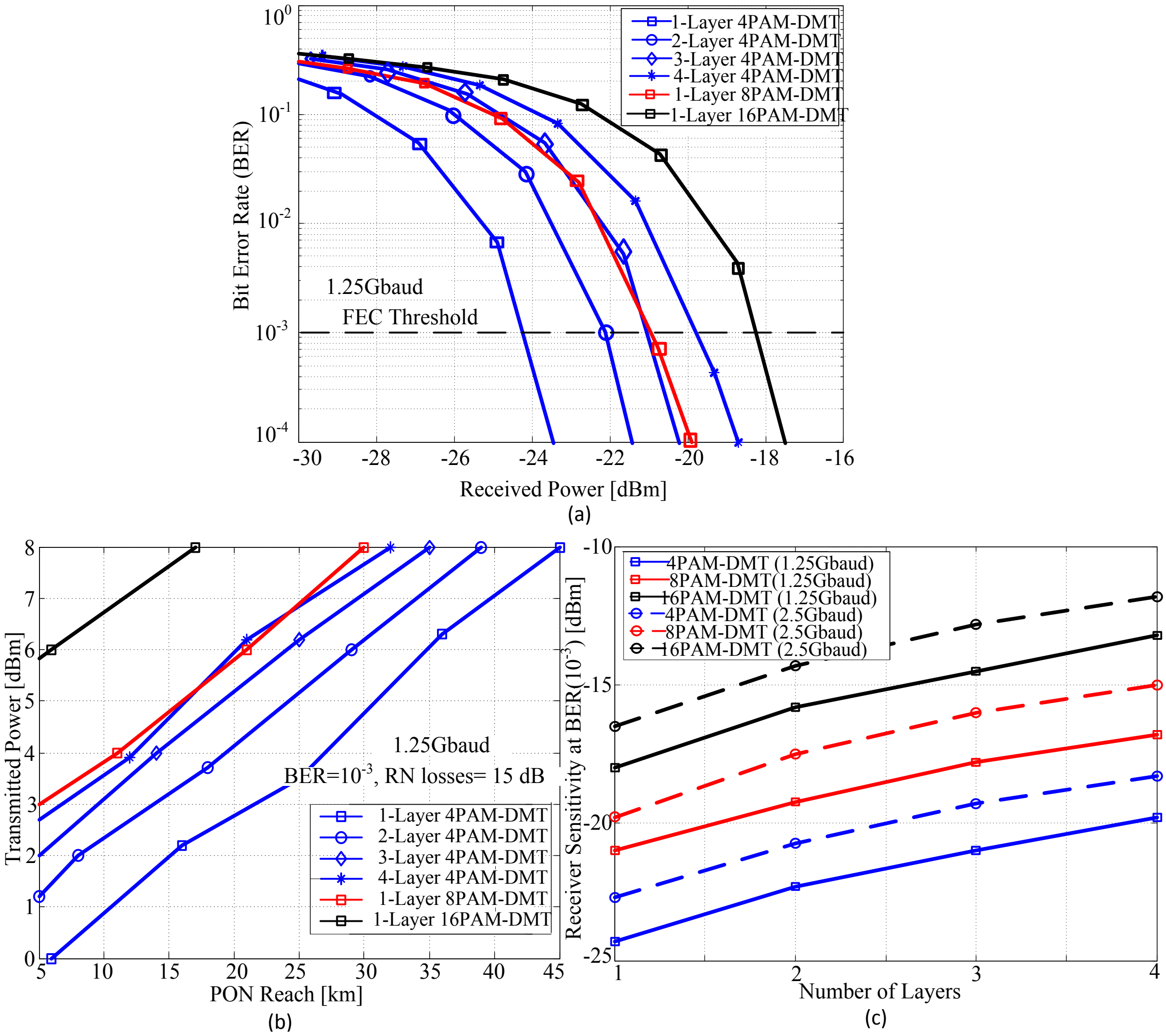


Figure 2. Basic PON architecture with emphasis on the downlink direction (simulation setup).

is used as shown in Fig. 1(b). For the first layer, the transmitted symbols can be directly detected from the imaginary part of the subcarriers. An additional IFFT block is used to regenerate the time-domain PAM-DMT signal of the previous layer, and then it will be subtracted from the received time domain signal to remove the clipping distortion from the upper layers that falls on the real part of X_k.

3. SIMULATION AND PERFORMANCE EVALUATION OVER A PON LINK

Layered PAM-DMT signal with 512-FFT length is generated using Matlab and passed to Optisystem to directly modulate a 1550 nm EML with output power of 5 dBm at 1.25Gbaud. The signal is then passed through 20 km of optical fiber as in Fig. 2. Fig. 3(a) shows that 2-layer 4PAM-DMT outperforms the 1-layer 8PAM-DMT by 1.25 dB in terms of the received power at bit-error rate BER=10^{-3} with same spectral efficiency. In addition, 3-layer 4PAM-DMT outperforms 1-layer 16PAM-DMT by 3 dB with 87.5% of its spectral efficiency, while 1.8 dB improvement using 4-layer 4PAM-DMT with 93.75% of 1-layer 16PAM-DMT spectral efficiency. Therefore, layered PAM-DMT with lower modulation order shows a better performance than the conventional PAM-DMT for the same spectral efficiency. Improvement in the PON reach using the proposed scheme shown in Fig. 3(b), where RN losses for 32 ONUs were considered. It can be seen that increasing the number of layers



(a)

(b)

(c)

Figure 3: (a) BER versus received power;(b) PON reach versus transmitted power at1.25Gbaud; (c) Receiver sensitivity versus number of layers at 1.25 and 2.5Gbaud.

is better than increasing modulation order for the same spectral efficiency. For example, at 8-dBm launch power, the PON reach of 4-layer 4PAM-DMT exceeds the 1-layer 16PAM-DMT by 15 km. From Fig. 3(c), it can be summarized that, for any modulation order and using 4-layer PAM-DMT, the spectral efficiency can be improved by 87.5% compared to conventional PAM-DMT with the same modulation order and less than 5 dB loss in the receiver sensitivity is needed.

Computational complexity of layered PAM-DMT transmitter C_{TX} is given in (5) [7], which is less than twice the conventional PAM-DMT complexity similar to layered ACO-OFDM in [5]. At the receiver, the complexity C_{RX} would be as in (6), which is less than 4 times the conventional system complexity when using the maximum possible number of layers. This is acceptable considering the spectral efficiency improvement.

$$C_{TX} = \sum_{l=1}^{L} O\left(\frac{N}{2^{l-1}} \log_2 \frac{N}{2^{l-1}}\right) \tag{5}$$

$$C_{RX} = O\left(\frac{N}{2^{L-1}} \log_2 \frac{N}{2^{L-1}}\right) + 2\sum_{l=1}^{L-1} O\left(\frac{N}{2^{l-1}} \log_2 \frac{N}{2^{l-1}}\right) \tag{6}$$

4. CONCLUSIONS

A spectrally efficient PAM-DMT scheme has been proposed for NG-PONs. In this scheme, both the real and imaginary parts of the subcarriers can be modulated with the PAM symbols using different layers of different IFFT sizes. Enhancement in the spectral efficiency can be achieved when compared to the conventional PAM-DMT systems. In addition, improvements in both the receiver sensitivity and PON reach have been reported using the proposed scheme when compared to the conventional PAM-DMT system for the same spectral efficiency.

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REFERENCES

[1] N. Cvijetic: OFDM for next-generation optical access networks, *J. Lightwave Technology*, vol. 30, no. 4, pp. 384-398, Feb. 2012.

[2] J. Armstrong: OFDM for optical communications, *J. Lightwave Technology*, vol. 27, no. 3, pp. 189-204, Feb. 2009.

[3] J. Armstrong and A. Lowery: Power efficient optical OFDM, *Electronics Letters*, vol. 42, no. 6, pp. 370-372, Mar. 2006.

[4] J. Armstrong and B. J. C. Schmidt: Comparison of asymmetrically clipped optical OFDM and DC-Biased optical OFDM in AWGN, *IEEE Communications Letters*, vol. 12, no. 5, pp. 343-345, May 2008.

[5] Qi Wang *et al.*: Layered ACO-OFDM for intensity-modulated direct-detection optical wireless transmission, *Optics Express,* vol. 23, no. 9, pp. 12382-12393, 2015.

[6] S. C. J. Lee *et al.*: PAM-DMT for intensity-modulated and direct-detection optical communication systems, *IEEE Photonics Technology Letters,* vol. 21, no. 23, pp. 1749-1751, 2009.

[7] A. V. Oppenheim, W. S. Ronald, and R. B. John: *Discrete-Time Signal Processing*, 3rd ed., Prentice-Hall, 1999.