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Citation for published version (APA):

Hong, M. K., Tran, N. C., Shi, Y., Tangdiongga, E., & Koonen, A. M. J. (2011). 10Gb/s transmission over 20km single fiber link using 1GHz RSOA by discrete multitone with multiple access. In *Proceedings of the 37th European Conference on Optical Communication (ECOC 2011) 18 - 22 September 2011, Geneva, Switzerland* [6065881] Optical Society of America (OSA). <https://doi.org/10.1364/ECOC.2011.Th.11.C.3>

DOI:

[10.1364/ECOC.2011.Th.11.C.3](https://doi.org/10.1364/ECOC.2011.Th.11.C.3)

Document status and date:

Published: 30/11/2011

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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10Gb/s Transmission over 20km Single Fiber Link using 1GHz RSOA by Discrete Multitone with Multiple Access

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Abstract: We demonstrate a novel 10Gb/s 20km single fiber transmission link based on a remotely fed 1GHz-bandwidth-limited RSOA. Adaptive loading with discrete multitone was applied. We also report flexible-bandwidth-allocated multiple access based on the proposed idea.

OCIS codes: (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems

1. Introduction

A colorless optical network unit (ONU) is an inevitable solution because the same transceiver can be used in every ONU regardless which wavelength channel it has to process. A reflective semiconductor optical amplifier (RSOA) is one of the most promising options to realize the colorless ONU [1]. However, most commercially available RSOAs are bandwidth limited to 1GHz, which restricts their application for >10-G PONs.

Electrical equalization techniques are commonly used to overcome the bandwidth limitation of the RSOA [2-5]. However, they require wavelength detuning with the optical filter devices [2], or a specifically designed RSOA module and electrical circuit [3-5] to optimize the performance. Most of all, the electrical equalization needs to be carefully tuned to chromatic dispersion. In addition, when these equalization techniques are to be applied to an RSOA which is remotely-fed through a single fiber link, it is impossible to maintain a good performance due to a reflection noise. Most studies have been demonstrated in an optical back-to-back case [4] and in a dual-fiber link [5] which means the RSOA was separately fed by a continuous wave (CW) light source locally or through a separate fiber. These implementations are fairly different from practical scenarios and therefore, these could increase the system costs at the ONUs. Moreover, their goals are mainly focused on multi Gb/s transmission. There is no multiple access scheme for wavelength-sharing which is another must-have feature for the next-generation PONs. Subcarrier multiplexing (SCM) and time division multiplexing (TDM) techniques would be alternatives for the multiple access. However, the performance of SCM could be severely degraded by optical beat noise because in most cases, SCM is implemented by means of independent light sources in the ONUs. In addition, TDM requires strict time synchronization, which becomes tougher at higher data capacity and at a larger number of ONUs.

The baseband version of orthogonal frequency division multiplexing (OFDM), discrete multitone (DMT), has been widely used due to its high spectral efficiency. Employing the power- and bit-loading algorithm, as described in [7], in combination with multi-level mapping such as M-ary quadrature amplitude modulation (M-QAM), DMT enables us to reach multiple Gb/s for bandwidth-limited transmission systems. Ref. [6] has demonstrated the use of this modulation format to achieve 7.5-Gb/s throughput by a locally-fed 1-GHz RSOA.

In this paper, we focus on a single fiber 20-km link with reflection noise in which 1-GHz RSOAs are remotely fed from the OLT. In addition, we use DMT to maximize the link capacity with respect to the available bandwidth in order to allow multiple ONUs sending their upstream data exactly at the same wavelength. Each ONU was allocated a certain number of DMT subcarriers to minimize interference. We experimentally demonstrated a proof-of-concept setup with two ONUs providing access with symmetrical and asymmetrical bandwidth allocation. The performance was analyzed by offline processing using a digital phosphor oscilloscope (DPO) and a MATLAB[®] code. The throughput for all cases was approximately 10 Gb/s with BER<10⁻³.

2. Operational principle of multiple access, experiments and discussions

Fig. 1 (a) briefly shows the proposed scheme for the flexible bandwidth allocation of DMT-based multiple access in case of two ONUs. An OLT provides a common CW wavelength channel of λ_1 to ONU 1 and 2. This seed signal is transmitted through a single SMF link and distributed to each ONU by a power splitter. For each distribution, the seed signal is injected into the RSOA and modulated for the upstream transmission. At this point, the parallel-mapped signal is allocated to a certain number of DMT subcarriers according to the designated ONU. Some of the DMT subcarriers are zero-padded as a guard band to minimize the interference between two ONUs. The modulated upstream signal from each ONU is combined and retransmitted through the single SMF link and recovered at the OLT according to the designated DMT subcarrier allocated to that ONU. This DMT subcarrier allocation is simply implemented digitally in frequency domain. ONUs share the same wavelength which is remotely fed by the OLT. Therefore, the proposed multiple access system could be free from optical beat noise and from strict time synchronization problems.

Fig. 1 (b) represents the experimental setup applying the concept in Fig 1 (a) employing the DMT technique. Off-line processing enables us to collect the data independently from two ONUs using a single RSOA. A CW optical source was realized by a tunable light source (TLS) at 1550nm with an output optical power of 5.8dBm. This

optical power was launched into a 20-km SMF link through an optical circulator (OC)1. OC2 was used to separate and monitor the input optical power of the RSOA without affecting the RSOA output. A polarization controller (PC) was used to optimize the input polarization state of the RSOA. Its -3dB modulation bandwidth was reported as 1.2GHz from its official datasheet (model: CIP SOA-R-C-7S-FCA). In the experiment, it was operated with a bias current and a temperature of 50mA and 20°C. In this condition, the measured -3dB modulation bandwidth was smaller than 1.2GHz as shown in the inset of Fig. 1. The adaptively loaded DMT signal was generated by MATLAB[®] and extracted by an arbitrary waveform generator (AWG: Tektronix 7122B) sampling at 8Gs/s. The number of DMT subcarriers was 512, ranging from DC to 4GHz, and the FFT size was 1024 according to Hermitian symmetry. For full modulation of the RSOA, the magnitude of the DMT signal from AWG was optimized by a variable electrical attenuator (VEA) and an amplifier. The DMT encoded optical signal from the RSOA was retransmitted to the same 20-km SMF link through OC2. After passing through OC2, this signal was delivered to a preamplifier, realized by an erbium doped fiber amplifier (EDFA) and optical isolators. The input optical power of the preamplifier was also monitored by an optical power meter (PM). In order to minimize the ASE noise, an optical bandpass filter (OBPF) with the center wavelength of 1550nm was used after the preamplifier. The input optical power of the received signal was also monitored. At this point, the input optical power of an optical receiver (HP 11982A) was maintained to -2dBm to provide experimental consistency. The optical receiver had a -3dB electrical bandwidth of 11GHz. The received DMT signal was captured by a DPO (Tektronix 72004B) with sampling speed of 50Gs/s. The received signal was evaluated by offline processing.

Fig. 1. (a) Operational principle of the proposed multiple access system based on DMT (b) experimental setup (Inset: frequency response of the RSOA: the bias current of 50mA, the input RSOA optical power of 0dBm)

Fig. 2. Adaptive bit and power loading results, probe EVM, bit-/power-loading profile and final BER performance per each subcarrier: (a) optical back-to-back (b) bi-directional 20km (c) constellation for the bi-directional 20km (upper side: 32QAM, lower side: 4QAM) (d) maximum achievable data rate with the input optical power of the RSOA (upper side) and the preamplifier (lower side)

Fig. 2 (a) and (b) represent the error vector magnitude (EVM) for the probe DMT signal to characterize the channel SNR, the adaptively loaded number of bits and power profile according to the channel SNR, and the BER performance for each DMT subcarrier in the optical back-to-back and the bi-directional 20km link transmission cases, respectively. As the probe DMT signal, the same level modulation of 16-QAM was used. It was verified that more bits were allocated to the subcarrier which had lower EVM (equivalent to higher SNR) and less bits were allocated to the subcarrier which had higher EVM (lower SNR). The channel power was loaded to each subcarrier according to the SNR performance for the given modulation format, so the power loading profile was quite different

from the bit-loading profile. Compared to the optical back-to-back, some subcarriers were discarded from the bit-loading because the SNR at those carriers was not high enough to transmit even a single bit. It makes sense because the EVM for the probe DMT signal at the discarded channels was higher than 50%. It has been reported that the EVM should be less than 46.03% to achieve a BER of 10^{-4} for binary phase shift keying (BPSK), equivalent to 1 bit allocation. Therefore, the maximum achievable data rate for the bi-directional link was severely degraded with a 6Gb/s penalty compared to the optical back-to-back as described in Fig. 2 (d). The most critical reason for this degradation was reflection noise from the bi-directional transmission. As shown in the case of the unidirectional 20km link in Fig. 2 (d) (measured in the case of the dash line in the experimental set up of Fig. 1), it was verified that this penalty could be dramatically suppressed to less than 2Gb/s because the reflection noise could be reduced in this case compared to the bi-directional line (in other words, a single fiber link). Nevertheless, it was still possible to achieve 10Gb/s transmission with an average BER less than 10^{-3} for the bi-directional 20km link when the input optical power of the RSOA and the preamplifier were higher than -9 and -12dBm, respectively. A good signal constellation was also clearly achievable in this condition as represented in Fig. 2 (c). The proposed system was able to transmit the 10Gb/s DMT signal with a proper optical SNR condition. The nonlinearity from the gain saturated operation of the RSOA was not the dominant factor to degrade the signal performance (the input optical power of the RSOA for the gain saturation was over -20dBm).

The multiple access was easily implemented by allocating the parallel-mapped data into a certain number of the DMT subcarriers. In addition, the data capacity provided for each ONU could be dynamically allocated by modifying the number of occupied subcarriers per ONU. The number of DMT subcarriers for a certain ONU should be carefully selected even in the case of a 50:50 capacity distribution. It is caused by the asymmetric bit-loading profile among the entire set of DMT subcarriers. Nevertheless, it was possible to accomplish a flexible bandwidth allocation for multiple access operation by using the proposed technique as shown in Fig. 3. We successfully demonstrated it for the 50:50 and 75:25 bandwidth-distributed conditions. In this operation, 10 subcarriers (equivalent to around 80MHz) were chosen as a guard band to prevent interference between the ONUs.

Fig. 3. Flexible bandwidth allocated multiple access operation measurements: bit-loading profile and power spectral density for (a) 50:50 (4.56:4.53Gb/s) allocation (b) 75:25 (6.89:2.21Gb/s) allocation (c) constellation for 50:50 allocation (left: ONU1-16QAM, right: ONU2-8QAM)

3. Conclusion

We successfully demonstrated a novel 10Gb/s 20km single fiber transmission link in which a 1GHz RSOA is remotely fed from the OLT. The DMT technique with adaptive loading algorithm was employed to overcome the bandwidth limitation of the RSOA. We reported a proof-of-concept experiment to show the feasibility of the flexible bandwidth allocated multiple access function for the case of two ONUs. This concept also allows to accommodate more than two ONUs. To the best of our knowledge, the proposed transmission link is the first multi-Gb/s demonstration based on the realistic scenarios of a single fiber link with a remotely fed, commercially available 1GHz RSOA, opening the possibility of multiple access.

This research is partly funded by the European Commission FP7 program ICT-212352 ALPHA, ICT-224402 EUROFOS and Yonsei University Institute of TMS Information Technology, a Brain Korea 21 program, Korea.

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