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Pulse patterning effect in optical pulse division multiplexing for flexible single wavelength multiple access optical network

Sun-Young Jung, Chang-Hun Kim, Sang-Kook Han*

Department of Electrical & Electronic Engineering, Yonsei University, 50 Yonsei-ro, Seodaemum-gu, Seoul 120-749, Republic of Korea

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ABSTRACT

A demand for high spectral efficiency requires multiple access within a single wavelength, but the uplink signals are significantly degraded because of optical beat interference (OBI) in intensity modulation/direct detection system. An optical pulse division multiplexing (OPDM) technique was proposed that could effectively reduce the OBI via a simple method as long as near-orthogonality is satisfied, but the condition was strict, and thus, the number of multiplexing units was very limited. We propose pulse pattern enhanced OPDM (e-OPDM) to reduce the OBI and improve the flexibility in multiple access within a single wavelength. The performance of the e-OPDM and patterning effect are experimentally verified after 23-km single mode fiber transmission. By employing pulse patterning in OPDM, the tight requirement was relaxed by extending the optical delay dynamic range. This could support more number of access with reduced OBI, which could eventually enhance a multiple access function.

1. Introduction

The enormously increased data traffic with limited frequency resources requires a spectrum-efficient transmission technique for a wireless access network. Orthogonal frequency division multiplexing (OFDM) with adaptive modulation has become a standard for long-term-evolution-advanced (LTE-A) in wireless communication owing to its high spectral efficiency (SE) [1]. Even in an optical access network, a spectrum efficient technique that can be applied within a single wavelength channel is required due to the saturated bandwidth of optical devices, although the fiber channel has a larger bandwidth than a wireless channel. Thus, OFDM-based passive optical networks (PONs) have been actively researched. Moreover, so-called dynamic bandwidth allocation (DBA) can be flexibly realized in a single wavelength by assigning subcarriers to the optical network unit (ONU) in OFDM-based multiple access (OFDMA) [2].

In OFDMA-PON, down link transmission from the optical line terminal (OLT) to the ONU is stable, similar to a point-to-point link. However, there are critical issues in uplink multiple access due to the optical path difference among ONUs, which causes a timing offset effect [3,4] and optical beat interference (OBI) [5–12]. The timing offset impacts the boundary subcarriers between ONUs by breaking the orthogonality. It can be reduced by inserting a frequency guard or extending the cyclic prefix (CP) length. In our previous work, the timing offset effect was effectively mitigated by employing filter bank-based multicarrier (FBMC) with asynchronous reception [4]. In comparison, OBI has a more serious influence than the timing offset effect because it generates a relatively large interference noise across a whole signal band. The OBI is generated when multiple optical carriers from different ONUs are transmitted in a single wavelength channel. Although multiple optical carriers have the same nominal wavelength, photons are generated with slightly different wavelengths depending on the linewidth of the optical source. Because of the square law detection of the photo diode (PD), simultaneously received multiple optical sources cause carrier-to-carrier beating. The center frequency of OBI is determined by the wavelength difference among the optical carriers and the shape of OBI is determined via the convolution among the power spectral densities (PSDs) of the optical fields [5,6]. Thus, when a laser diode (LD) is used as an optical source, OBI is generated at baseband by forming a Lorentzian shape, as shown in Fig. 1. This interrupts a proper signal detection by causing a very large intensity fluctuation in the uplink signal band.

Techniques for reducing OBI have been proposed [7–12]. Wavelength separation [7,8] can effectively migrate OBI to out of the signal band by up-converting the center frequency of OBI but requires every ONU to use a different nominal wavelength. Carrier suppression with coherent detection [9] can avoid OBI by eliminating the beating source but is not an intensity modulation/direct detection (IM/DD) system. Spectrum broadening (SB) [10,11] can simply flattening the OBI spectrum by spreading a convolution of PSDs over a broad spectral

* Corresponding author.
E-mail address: skhan@yonsei.ac.kr (S.-K. Han).

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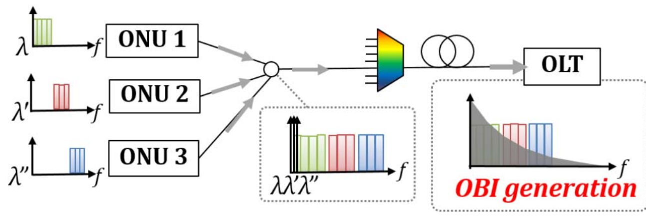

Fig. 1. OBI generation in IM/DD-OFDMA-PON uplink multiple access within a single nominal wavelength channel.

range but is limited considering the transmission distance and wavelength division multiplexing (WDM) channel width. Considering SB and time domain regularity, optical pulse division multiplexing (OPDM) was proposed [12]. It was experimentally verified that by employing OPDM-based OBI reduction to IM/DD-OFDMA-PON uplink multiple access within a single nominal wavelength after 20-km single mode fiber (SMF) transmission, the achievable SE was improved from 0.37 to 3.8 bit/s/Hz. This could minimize and flatten the OBI as long as the time domain requirement is satisfied, but the range of the condition for satisfying the signal quality is very limited.

In this paper, we propose a pulse pattern enhanced OPDM (e-OPDM) technique by shaping the optical pulse train to simply reduce the OBI and at the same time cope with the limitation of OPDM and improve the flexibility of multiple access in the OFDMA-PON uplink. In source seeding-based colorless multiple access, the performance of the proposed e-OPDM after 23-km SMF transmission was experimentally verified with respect to the waveforms, spectra, channel error vector magnitude (EVM), and SE after adaptive modulation. By using the proposed e-OPDM, the requirement to ensure the signal quality can be relaxed, which means that uplink multiple access can be more easily realized without a strict requirement and the number of multiplexed ONUs within a single wavelength channel can be increased with reduced OBI.

2. Operational principle

A basic schematic of an IM/DD-OFDMA-PON is presented in Fig. 1. The signal bandwidth is allocated by assigning subcarriers to individual ONUs. Due to the linewidth of the LD and the modulation condition, the generated optical carriers of each ONU differ slightly, although they have the same nominal wavelength. After transmission, these different uplink optical carriers are simultaneously detected at the OLT, which generates a carrier-to-carrier beating so-called OBI due to the square law detection of the PD. The center frequency of OBI is located at the wavelength difference among the optical carriers, and the shape of the OBI is formed via convolution among the PSDs of the optical fields [5,6]. If the LD is used for the optical source of the ONU and multiple ONUs transmit at the same nominal wavelength, OBI is generated at the baseband by forming a Lorentzian shape, as shown in Fig. 1.

In Fig. 2, a schematic of a source seeding-based colorless OFDMA-PON and the process of the proposed e-OPDM-based OBI reduction are presented from the viewpoint of the frequency domain. A basic process of the proposed e-OPDM is same with the previous OPDM [12] except an increased number of ONUs. In the source seeding system, a single optical source from the remote node is fed to several ONUs and independently modulated at every ONU using an optical modulator. In this case, a reflective modulator such as a reflective semiconductor optical amplifier (RSOA) is suitable for colorless operation. After the ONUs modulate their own OFDMA signal, the uplink multiple signals are transmitted through a single nominal wavelength channel. As shown in Fig. 2(a), OBI is generated similarly in the source seeding system with an individual source generating system, because the reflected optical carriers have time delay caused by the optical path difference among ONUs. To simply reduce the OBI, the proposed e-OPDM based on a directly modulated radio frequency (RF) clipping tone (CT) can be employed in this system. In the frequency domain, the e-OPDM technique plays the same role as the SB technique [11], which considers that a broad source can spread the convolution of PSDs over a broad spectral range. The LD for the seeding source is directly modulated by the RF CT, which generates an RF tone and harmonics because intensity modulation is a nonlinear process. As shown in Fig. 2(b), by using a directly modulated RF tone before source seeding, a partial power of OBI can be up-converted from the baseband to the RF tone and harmonics. An RF CT with sufficient power can increase the amplitude of harmonics and generate nonlinear components, causing the optical spectrum to be broadened. As shown in Fig. 2(c), the baseband OBI can be up-converted to every harmonic and nonlinear component because the large harmonics contribute to a beat process, which can spread the OBI over a broad range by forming a flattened spectrum. Thus, the e-OPDM technique can make OBI additive white noise in the frequency domain.

Fig. 3 presents a time domain illustration of the proposed e-OPDM in source seeding-based OFDMA-PON uplink multiple access. In the time domain, there is a difference between e-OPDM (OPDM) and the SB technique. The directly modulated RF CT gives rise to a periodic power variation in the time domain as well as it causes the optical source to be broadened in the frequency domain. The periodic power variation appears to be an optical pulse train, although it is not perfectly on–off. For simplicity, the seeding source can be assumed as an ideal rectangular pulse train whose duty cycle (k) is 50%, which is same as the previous OPDM. In the case of two ONUs, as illustrated in Fig. 4, it can be expressed as

$$p_1(t) = p_1(t-T) \qquad p_1(t) = \begin{cases} 1, & (0 \le t < T/2) \\ 0, & (T/2 \le t < T) \end{cases}, \qquad p_2(t) = p_1(t-d_{12}) \tag{1}$$

where T is a repetition cycle, $p_n(t)$ is an ideal rectangular pulse train fed to the n^{th} ONU, and d_{1n} is the optical delay between the 1st ONU and n^{th}

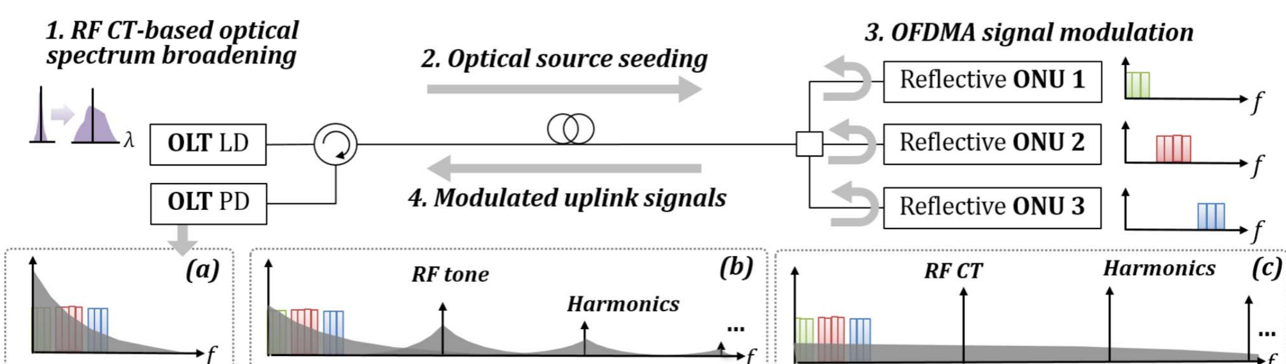

Fig. 2. Schematic of e-OPDM-based OBI reduction in a source seeding system and received RF spectra. (a) Without e-OPDM. (b) With directly modulated RF tone (m < 1). (c) With directly modulated RF CT (m > 1).