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Efficient use of Bandwidth by WDM-OFDM-PON Based on Compatible SSB Technique

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Abstract*— Increasing demand of bandwidth can be reached by employing WDM-OFDM-PON for downstream transmission, based on a tunable mode locked comb source. The WDM-OFDM-PON based on compatible SSB technique provides the required bandwidth for downstream transmission. The 12.75 Gbps compatible SSB OFDM signal is used to modulate 10 comb tones separated by 10 GHz. A spectral efficiency of 1.275 bps/Hz was achieved in conjunction with the use of low complexity electronics. Transmission over 50 km and 87 km of standard single mode fibre was successfully demonstrated. The bit error rate for transmission over 50km fibre optic cable can be reduced to a maximum extent. The transmission over the channels after 87km achieved performance below the 20% FEC limit.

Keywords*— Multi-carrier transmitter, orthogonal frequency division multiplexing (OFDM), passive optical networks (PON), wavelength division multiplexing (WDM).

INTRODUCTION

Demand for bandwidth shows no sign of reducing and is pushing service providers to deploy long-haul, metro and access networks with increased capacity. Wavelength division multiplexing technology has been successfully used to expand capacity in these optical systems and meet increasing bandwidth requirements. Recently, orthogonal frequency division multiplexing has attracted much research interest as a modulation technique due to its high spectral efficiency coupled with its ability to overcome the effects of chromatic dispersion [1]. High spectral efficiency is a consequence of the overlapping of subcarriers, whilst arbitrary amounts of dispersion can be handled by using a cyclic prefix (CP) which facilitates the construction of a simple maximum likelihood equalizer in the frequency domain.

The use of OFDM in optical access networks has been extensively investigated in recent years for both downstream (DS) and upstream (US) data transmission as such systems provide high dedicated bandwidth to the user [2], [3]. Based on the system requirements, various solutions, such as using a single OFDM carrier per user, to assigning a wavelength to each user have been proposed. In many of these proposed WDM-OFDM-PON solutions, single side-band (SSB) OFDM modulation generated by optical filtering of a double side- band (DSB) OFDM signal at the transmitter [3]-[5] is used together with direct detection for downstream transmission. DSB OFDM suffers from chromatic dispersion induced power fading [6], [7] and requires a larger spacing between optical carriers in a WDM-PON scenario compared to SSB OFDM signals. However, a standard SSB OFDM signal generation increases the cost of the analog equipment as a narrow optical filter is typically required to eliminate one of the side-bands at the transmitter. The compatible SSB OFDM modulation technique [8]-[10] overcomes the disadvantages of both methods mentioned above. However, the high carrier-to-signal ratio, which is a property of intensity modulated OFDM signals such as compatible SSB OFDM, makes these systems vulnerable to optical noise [10] and requires the use of optical comb sources which exhibit excellent signal to noise ratio on each comb line.

In this paper, we demonstrate downstream transmission of compatible SSB OFDM in a WDM-PON where a tunable mode-locked laser (TMLL) is employed as a multi-carrier transmitter. Ten comb tones, separated by 10GHz, are filtered from the TMLL comb and each tone is modulated with a 12.75 Gb/s SSB OFDM signal. The performance of the system is evaluated under back-to-back (B2B) and standard single mode fiber (SSMF) transmission scenarios (50 and 87 km). Results obtained show excellent performance of the proposed system with less than a 1 dB penalty at a bit error rate (BER) of $3{\cdot}10^{-3}$ after 50 km transmission compared to the B2B case. Furthermore, BER measurements after 87 km transmission without inline amplification show that all the channels achieved performance below the 20% FEC limit.

EXPERIMENTAL ANALYSIS

The experimental setup used for the WDM-OFDM-PON system is shown in Fig. 1. The optical line terminal (OLT) consists of a wavelength tunable mode locked semiconductor laser. A 10 GHz sinusoidal signal, derived from a signal generator, is amplified and applied to the TMLL to achieve active mode locking. The spectral output from the actively mode locked TMLL is a frequency comb consisting of about 40 tones spaced by 10 GHz, which exhibit spectral ripple of 10 dB. Tunability in free spectral range (FSR) of the used TMLL is limited (9-11 GHz). A bandwidth and wavelength tunable optical filter is then used to select 10 comb tones, separated from each other by 10 GHz, which exhibit a spectral ripple of less than 3 dB. An Erbium doped fiber amplifier (EDFA) is used to overcome the loss of the filter. In field installations, the generated comb lines would be separated by a de-multiplexer and each individual channel would be modulated independently.

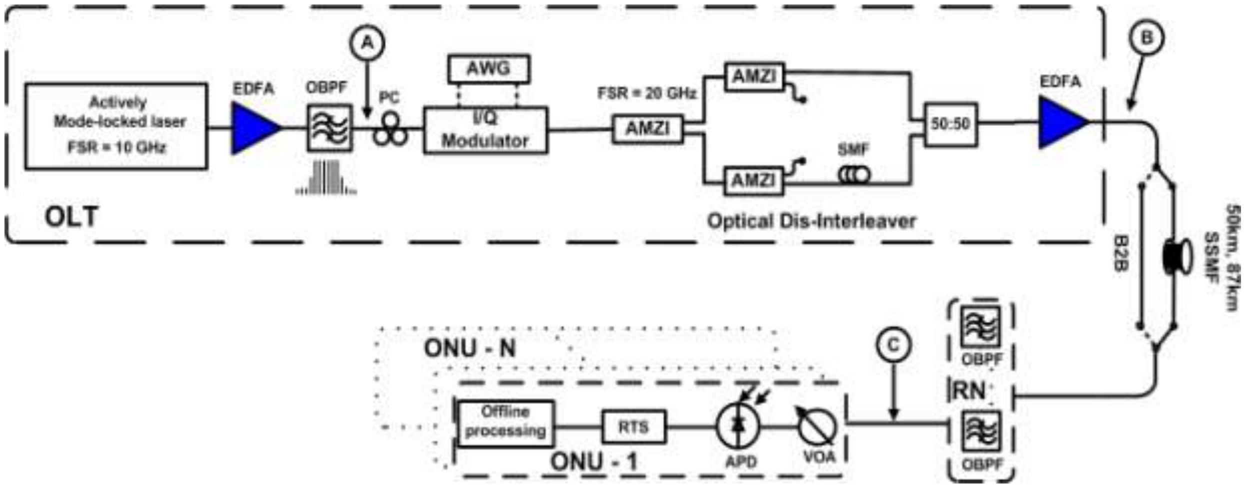


Fig. 1. Schematic of the experimental setup

Optical Band-Pass Filter (OBPF); Polarization Controller (PC); Arbitrary Waveform Generator (AWG); Asymmetric Mach Zehnder Interferometer (AMZI); Erbium Doped Fiber Amplifier (EDFA); Variable Optical Attenuator (VOA); Avalanche Photodetector (APD); Real Time Scope (RTS).
However, in this experiment all 10 comb tones are modulated by a single dual-drive Mach- Zehnder modulator (DD-MZM). The DD-MZM is biased at the quadrature point and then modulated with a compatible SSB OFDM signal waveform [8]-[10] derived from an arbitrary waveform generator (AWG).

The 12.75 Gb/s compatible SSB OFDM signal is composed of 77 subcarriers with 16QAM modulation format on each subcarrier, and an OFDM symbol rate of 39.06 MHz. The incorporation of the 7% (50 km transmission) or 20% (87 km transmission) forward error correction (FEC) overhead together with a cyclic prefix length of 6.25% of the IFFT size (which has 256 inputs) gives a net data rate of 11.2 Gb/s and 10 Gb/s, respectively. The total bandwidth of the signal is about 3 GHz.

The modulated signal is then passed through a set of tunable cascaded dis-interleavers based on asymmetric Mach Zehnder interferometers (AMZI), with a FSR of 20 GHz. The dis- interleaver separates the 10 optical comb tones into odd and even sub-channels with a 40 dB extinction ratio. The 5 even channels are subsequently passed through a 5 m de-correlation fiber patchcord, and then passively combined with the 5 odd channels.

The combined signals are then optically amplified with an EDFA which operates in constant power mode, prior to being characterized by measuring the BER as a function of the received optical power under B2B and, 50 and 87 km SSMF transmission scenarios. At the remote node (RN) the desired channel is filtered with a narrow optical band-pass filter (OBPF). In a practical scenario, an appropriate de- multiplexer would be used instead of a single optical filter. Depending on system requirements, a single wavelength can be dedicated per user, or further divided among users after detection. The filtered channel is detected within the optical network unit (ONU) by using a 10 GHz receiver that consists of an avalanche photodetector (APD) and an integrated trans- impedance amplifier (TIA). The received signal is captured with a real time oscilloscope operating at 50 GSa/s. Digital processing of the received signal and bit error rate calculations are performed offline using Matlab.

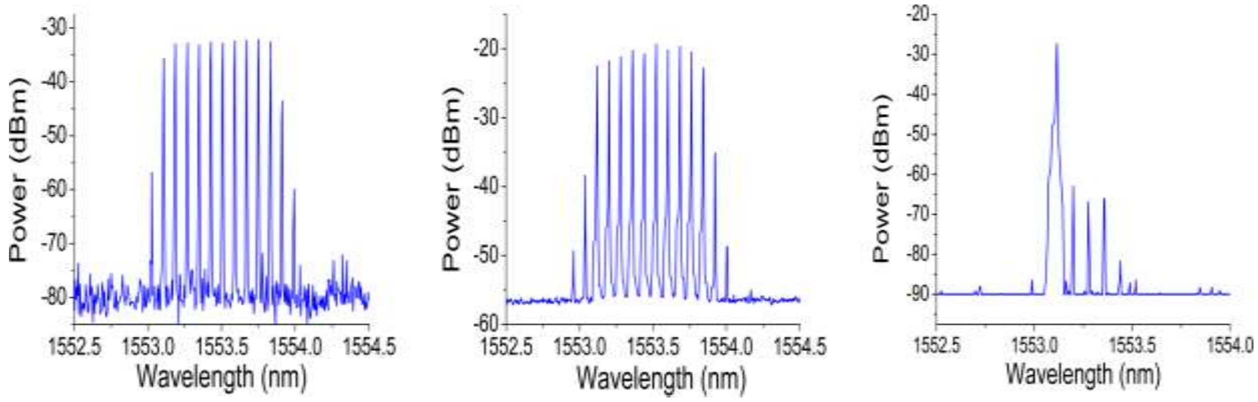


Fig. 2. Optical spectrum of a) 10 filtered optical comb tones; b) modulated optical carriers; and c) single channel filtered carrier at the receiver.

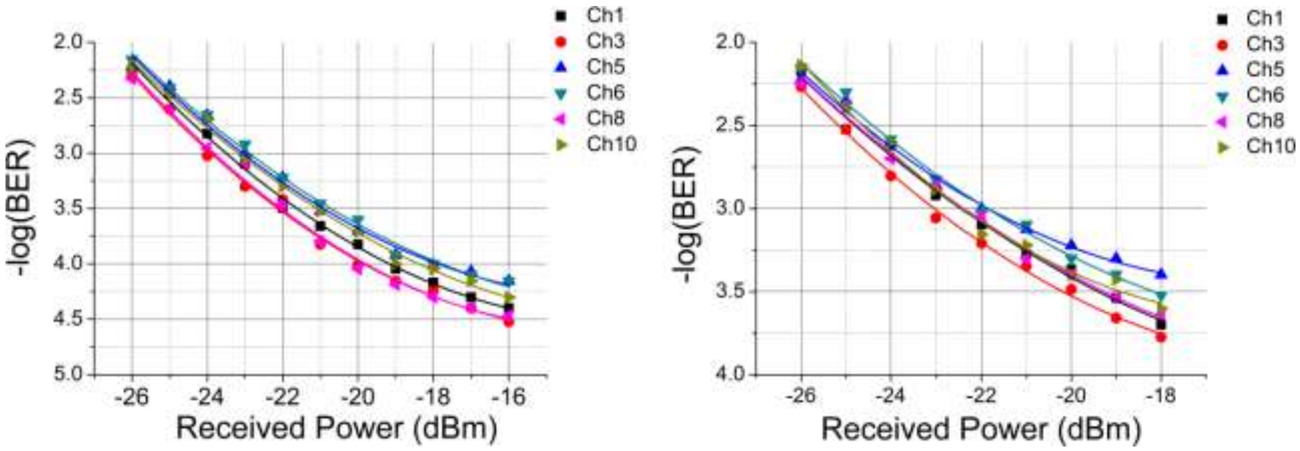


Fig. 3. –log(BER) versus received optical power for a) back-to-back and b) transmission over 50 km of SSMF.

RESULT AND DISCUSSION

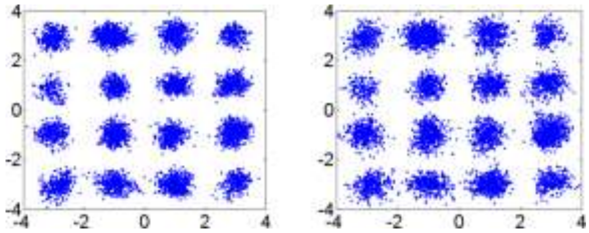
The high carrier-to-signal ratio is a property of intensity modulated OFDM signals, such as compatible SSB OFDM. The high power in the carrier relative to the signal is determined by peak-to-average-power ratio (PAPR) of the OFDM signal [8]. In order to ensure the linear operation of a MZM, a small modulation index of the input signal is required, which will cause that signal sideband to have much lower power than that of the carrier. Hence, such systems will be more vulnerable to optical noise [10]. Therefore, the choice of an optimal optical multi-carrier source (such as the TMLL) which exhibits a high signal-to-noise ratio (~55 dB) on each unmodulated line can assure excellent performance of the system.

Optical spectra at different stages are shown in Fig. 2. The 10 filtered comb tones are shown in Fig. 2a (measured at point A in Fig. 1), whilst the signal after modulation (at point B in Fig. 1) is presented in Fig. 2b. This figure clearly illustrates the compatible SSB modulation and high carrier-to-signal ratio. Fig. 2c depicts one filtered channel at the receiver prior to detection (point C on Fig. 1).

The obtained experimental results are presented in Fig 3. In both cases, B2B and 50 km SSMF transmission, the power at the receiver is limited, with the aid of a variable optical attenuator (VOA), to a maximum of -15 dBm due to the low saturation power of the APD. In both B2B and 50 km transmission cases, the middle channels exhibit worse performance compared to outer channels mainly due to the higher cross-talk. However, the power penalty between the outer channels can be attributed to the power asymmetry of the frequency comb and the interference from the non-ideally suppressed unwanted sidebands during de-correlation. The optical band-pass filter at the receiver is optimized to get the best performance for the desired channel, i.e. finding an optimum level between carrier-to-signal ratio and suppression of neighboring channels. Fig. 4 shows constellations for the 3rd channel (Ch3 in Fig. 3) measured for various received powers in the B2B and 50 km scenarios.

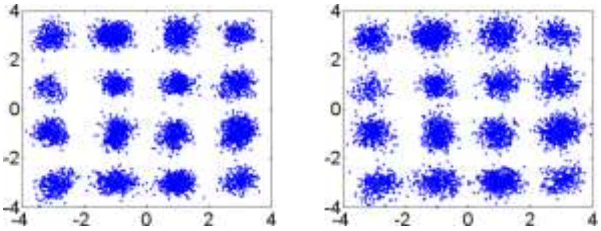
Compatible SSB WDM-OFDM-PON shows less than 1 dB power penalty at a 7% FEC limit ($BER=3\cdot10^{-3}$) after transmission over 50 km SSMF compared to the B2B case, for all channels. Evidently, effects of transmission impairments on the proposed system are very low. This is partially due to the fact that dispersive fading is negligible for SSB OFDM signals. Furthermore, the optical launch power (12 dBm and 15 dBm for 50 km and 87 km transmission respectively) is controlled in order to avoid significant non-linear distortions.

$BER= 3.5\cdot10^{-5}$ (P = − 16 dBm, B2B) $BER= 1\cdot10^{-3}$ (P = − 24 dBm, B2B)



(a)   (b)

$BER= 2\cdot10^{-4}$ (P = − 18 dBm, 50 km) $BER= 9\cdot10^{-4}$ (P = − 23 dBm, 50km)



(c)   (d)

Fig. 4. Constellations obtained for the 3rd channel for various received powers in the B2B and 50 km scenarios.

System performance after transmission over 87 km of SSMF is further investigated and results obtained are given in Fig. 5. The BER of each channel is measured at a maximum received power of − 28 dBm due to the additional power loss caused by the extended fiber transmission. However, the results obtained show that a BER below the 20% FEC limit ($BER=2\cdot10^{-2}$) is achieved on all channels.

The narrow bandwidth of the OFDM signal (~3 GHz) and a channel spacing of 10 GHz provide sufficient spacing for upstream data transmission. One possible solution, which would provide efficient usage of the available bandwidth, would be to employ low cost tunable lasers [11] at the ONUs. Taking into account the allowable level of complexity, the desired transmission distance, and the required baud rate at each ONU, an optimum modulation format with a maximum spectral bandwidth of 5 GHz could be chosen, and the upstream data could be placed between two downstream channels.

Another solution which can enable symmetric WDM- OFDMA-PON [12] can be realized by providing guard bands between DS and US signals. In such a scenario, a TMLL located at the OLT or RN can be used for US data transmission, at an offset wavelength relative to the TMLL used for DS transmission. At the ONUs, the compatible SSB OFDM signal would be modulated onto the optical carrier by the DD-MZM.

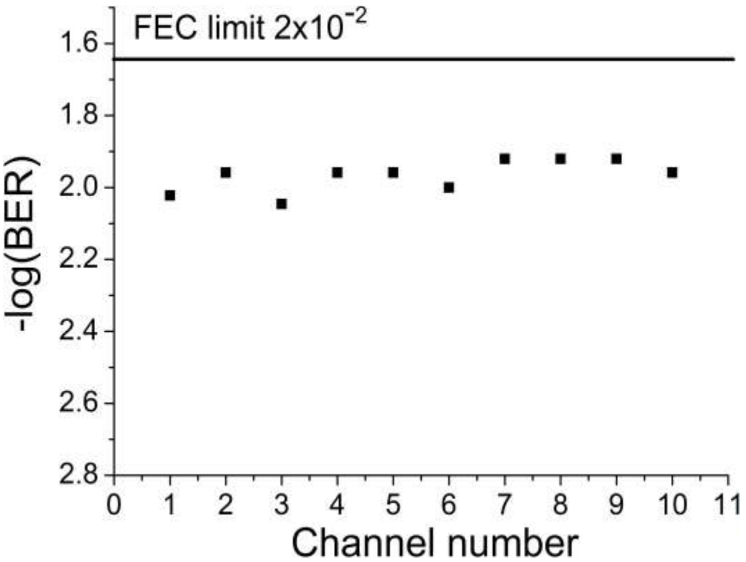


Fig. 5. Measured bit error rate for all 10 channels after 87 km transmission at received optical power of P = −28 dBm.

CONCLUSIONS

An approach for spectrally efficient transmission of optical OFDM signals employing a multi-carrier transmitter has been presented. Intensity modulated OFDM signals, such as compatible OFDM, exhibit high carrier-to-signal ratio which makes these systems vulnerable to optical noise and limits usage of optical multi-carrier transmitters. In this paper, we used for the first time, a TMLL as a multi-carrier transmitter in a WDM-OFDM-PON employing compatible SSB OFDM for downstream data transmission. Compatible SSB OFDM effectively overcomes the disadvantages associated with DSB OFDM; namely the dispersion induced power fading effect which is negligible in this case. Furthermore, the complexity of analog equipment required for the generation of standard SSB OFDM signal is reduced. A solution where one wavelength can serve one or multiple users based on requirements has been proposed, as well as possible solutions for upstream transmission. A power penalty of less than 1 dB at a $BER=3\cdot10^{-3}$ has been measured after 50 km transmission over SSMF. Transmission over 87 km is also investigated and the results obtained show the potential of the proposed technique. It should be noted that the use of higher speed electronics or the reduction of the TMLL FSR can be used to further enhance the spectral efficiency of the proposed system.

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