Offset Manchester coding for Rayleigh noise suppression in carrier-distributed WDM-PONs

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ABSTRACT

We propose a novel offset Manchester coding in upstream to simultaneously realize Rayleigh noise suppression and differential detection in a carrier-distributed wavelength division multiplexed passive optical network. Error-free transmission of 2.5-Gb/s upstream signals over 50-km standard single mode fiber is experimentally demonstrated, with a 7-dB enhanced tolerance to Rayleigh noise.

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1. Introduction

The wavelength-division-multiplexed passive optical network (WDM-PON) is a promising candidate for the next generation optical access network [1]. In a carrier-distributed WDM-PON, the upstream carriers are remotely distributed from the optical line terminal (OLT), thus eliminating wavelength-specific transmitters and wavelength management at the cost-sensitive optical network unit (ONU). To reduce the system cost, bidirectional transmission over single feeder fiber is highly desirable. However, the intrinsic Rayleigh backscattering (RBS) of the distributed optical carrier induces severe interferometric crosstalk to the upstream signal. The RBS, with a narrow spectrum, can be effectively suppressed by an optical notch filter. However specially designed upstream modulation formats are required to avoid the upstream signal itself being distorted by the notch filter [2,3]. Single-tone phase modulation or optical carrier suppression can also be used to suppress the RBS crosstalk [4,5]. The attention of the research community has recently turned to the electrical high-pass filter (HPF) based approach for RBS crosstalk suppression in WDM-PONs [6–9]. In this approach only 8B10B coding, electronic equalization or Manchester coding (MC) is required, thus resulting in only minor modifications to the PON structure.

In this paper, we propose an offset-Manchester coding (OMC) to suppress Rayleigh noise more effectively in the carrier-distributed WDM-PON and to simultaneously realize upstream differential detection, via a postdetection HPF. Compared with prior schemes using 8B10B coding or electronic equalization [6,7], albeit Manchester coding requires larger bandwidth it enables much easier clock extraction. The unique self-clocking property of Manchester coding together with differential detection enables burst-mode upstream detection [10], which is desirable in hybrid WDM/TDM-PONs. The Manchester encoder, an exclusive OR (XOR) gate, is also simpler than the 8B10B encoder. Unlike the 8B10B coding, no decoder is needed at the receiver side for Manchester coding. In addition, by further using OMC that is generated by offsetting data and clock signal before the XOR gate, the cutoff frequency of the HPF used to remove Rayleigh noise can be much higher than that using 8B10B coding, electronic equalization or MC [6–9], leading to more effective Rayleigh noise suppression and much relaxed requirement for the seed laser linewidth. The proposed scheme is also simpler than the prior scheme employing differential Manchester coding and self-homodyne coherent detection [11].

2. System architecture and operation principles

Fig. 1 illustrates the proposed loopback architecture. After the transmission in a 50-km standard single mode fiber (SMF), the optical carriers from the OLT are wavelength routed toward different ONUs, by an arrayed waveguide grating (AWG) at the remote node (RN). At the ONU, the CW light is modulated by a
reflective modulator driven by upstream data with OMC, before being sent back to the OLT. The received upstream signals are pre-amplified by a shared erbium-doped fiber amplifier (EDFA) before direct detection. A postdetection HPF is used to suppress Rayleigh noise and to simultaneously realize upstream differential detection.

For the signal with conventional Manchester coding, the low frequency components are significantly suppressed. Thus the MC-signal can pass through a properly designed HPF without compromising the signal quality. To further reduce low frequency components, we propose an OMC for the upstream signal. Fig. 2 indicates the encoding process for both MC and OMC signals. The MC signal is generated by an exclusive-OR (XOR) operation between the original binary signal and an aligned clock signal, whereas the OMC signal is generated by an XOR operation between the original binary signal and an offset clock signal (say with an offset of \( \tau \)). For comparison, the power spectral densities (PSD) of MC, OMC (offset = 40 ps or 80 ps) and NRZ signals are calculated and shown in Fig. 3. We can observe that for the OMC signal the low frequency component can be further suppressed compared to the MC signal. Thus for the OMC-signal, the cutoff frequency of the HPF can be higher. Note that in the previous schemes using 8B10B coding (bit rate: 1.25 Gb/s) or electronic equalization (bit rate: 2.5 Gb/s), the cutoff frequency of the HPF is as low as 10 MHz [6,7], whereas in this paper the cutoff frequency of the HPF is substantially increased to 164 MHz. The HPF also serves as a simple passive differentiator that converts the upstream Manchester encoded signal to its differentially detected version [10], with a fixed optimal threshold at zero level that is highly desirable for burst-mode detection. As the optical spectra of both the RBS and the upstream OMC-signal have strong low-frequency components, after detection the beating noise mainly distributes at the low frequency region and can be substantially suppressed by an electrical HPF. The 3-dB spectral width of the beating noise is roughly the double of the linewidth of the seed laser [7]. Thanks to the much higher cutoff frequency of the HPF in the proposed scheme, more beating noise can be removed. In addition, less expensive seed lasers with a relatively wider linewidth can be used.

![Fig. 1. Proposed loopback architecture using Manchester coding and postdetection electrical high-pass filter in upstream to suppress Rayleigh noise. The downstream channels are omitted here for simplicity.](image1)

![Fig. 2. (a) Encoding process for MC signal. (b) Encoding process for OMC signal.](image2)

![Fig. 3. Power spectral densities of MC, OMC (offset = 40 ps or 80 ps) and NRZ signals.](image3)

![Fig. 4. Experimental setup to investigate the Rayleigh-noise tolerance.](image4)

3. Experiment demonstration

We first investigated the upstream power penalty as a function of signal-to-crosstalk ratio (SCR) based on the experimental setup in Fig. 4, which is similar to that employed in [6]. Continuous-wave (CW) light at 1553.5 nm from a tunable laser diode (TLD) was split into two paths by a 3-dB coupler. In the upper path, Manchester data were first generated by the logic XOR operation of a non-return-to-zero (NRZ) 2.5-Gb/s \( 2^{31} - 1 \) pseudorandom binary sequence (PRBS) and a 2.5-GHz clock via a commercial XOR chip, and then used to drive a Mach–Zehnder modulator (MZM). The MC-signal was generated when the NRZ PRBS and the clock signal were well aligned, whereas the OMC-signal was generated when the NRZ PRBS and the clock signal were temporally offset by 74 ps. Following the MZM, a variable optical attenuator (VOA) was used to adjust the signal power to obtain different SCR values. In the lower path, the crosstalk signal was the RBS light from a 50-km SMF.
SMF, with a fixed power of $-33.4 \text{ dBm}$ measured after a polarization controller (PC). The PC was used to maximize the beating noise. The Manchester encoded signal and the crosstalk signal were then combined by a 3-dB coupler and fed into the upstream receiver, which consisted of an EDFA, a 100-GHz AWG (3-dB bandwidth $= 0.6 \text{ nm}$, insertion loss $= 4 \text{ dB}$), and a p-i-n receiver, followed by an electrical HPF with a 3-dB lower cutoff frequency of 164 MHz and a 1-dB upper cutoff frequency of 3 GHz. For comparison, the crosstalk tolerance of the NRZ signal was also investigated. In this case, the MZM was directly driven by the same NRZ 2.5-Gb/s $2^{21} - 1$ PRBS and the HPF was removed from the upstream receiver. Without removing the HPF, the detected eye diagram of the NRZ signal was completely closed due to baseline wandering.

Three conclusions can be derived from Fig. 5(a), which depicts the eye diagrams at different SCR levels. Firstly, the OMC-signal always has a wider eye opening than the MC-signal, as it has fewer low frequency components and is more robust to high pass filtering. Secondly, both the OMC-signal and the MC-signal are more resistant to the Rayleigh noise than the NRZ signal, as the majority of beating noise is suppressed by the HPF. Thirdly, in contrast to the NRZ signal for which the optimal threshold level decreases as the SCR decreases, the optimal threshold level of the Manchester signals is always fixed at zero level as the SCR decreases. The reason is that differential detection of the Manchester signal is simultaneously realized via the HPF that is used to suppress the beating noise.

The measured upstream power penalty ($\text{BER} = 10^{-9}$) at different SCR levels is shown in Fig. 5(b). In all BER measurements, the decision threshold level was fixed at zero level, which was an optimal threshold for all the three signals when there was no crosstalk. For a 2-dB power penalty at 2.5 Gb/s, by using OMC or MC the SCR can be reduced by 7 dB than using NRZ PRBS. Note that in the prior scheme using 8B10B coding [6], the SCR value for a 2-dB power penalty can only be reduced by 5 dB than using NRZ PRBS at 1.25 Gb/s.

We then experimentally demonstrated the proposed loopback scheme based on the architecture shown in Fig. 1. At the OLT, CW light at 1553.5 nm from a TLD with a power of 3-dBm was fed into a span of 50-km SMF through a circulator (from port 1 to port 2). An AWG (4-dB insertion loss) with a channel spacing of 0.8 nm and a 3-dB bandwidth of 0.6 nm was used at the RN. The input CW power to the ONU was $-11.5 \text{ dBm}$. At the ONU, the reflective modulator consisted of a circulator, an EDFA and a Mach–Zehnder modulator (MZM). In practical implementation, the reflective modulator could be a reflective electro absorption modulator integrated with a semiconductor optical amplifier (SOA) [12]. The upstream receiver here was the same as in Fig. 4, and was connected to the port 3 of the circulator at OLT. The BER measurement results are shown in Fig. 6. The ONU gain, defined as the power ratio between the output and the input signals at ONU, was fixed at 11.8 dB for all BER measurements shown in Fig. 6. We first investigated the dispersion tolerance of the upstream signals. Compared with the back-to-back cases, after transmission in 50-km dual feeder fibers (SMF), less than 0.6-dB dispersion-induced power penalty (at $\text{BER} = 10^{-9}$) is observed for both the OMC-signal and the MC-signal. Compared with dual-fiber transmission, around 4-dB power penalty is observed for both signals when single feeder fiber is used, due to residual Rayleigh noise. We also obtained that the Rayleigh noise induced power penalty could be further reduced to around 1 dB, when the ONU gain was increased to 15.6 dB. The receiver sensitivity of the OMC-signal is improved by around 2 dB compared with that of the MC-signal as shown in Fig. 6. Without the HPF, both signals show an error floor between...
10^{-4} and 10^{-5}. Similarly, for NRZ signal, error floors at \(10^{-5}\) and \(10^{-7}\) are observed for the fixed and the optimized decision thresholds, respectively. Note that dynamic threshold optimization is challenging in practical implementation, thus in all BER measurements for both the OMC-signal and the MC-signal, the decision threshold level was always fixed at zero level, without dynamic threshold optimization.

4. Conclusion

We propose an offset Manchester coding to simultaneously achieve Rayleigh noise suppression and upstream differential detection for WDM-PONs. Error-free transmission of 2.5-Gb/s upstream signals in 50-km SMF is demonstrated, with a 7-dB enhanced tolerance to Rayleigh noise. The unique self-clocking property of Manchester coding together with differential detection facilitates new designs of future hybrid WDM/TDM-PONs, in which burst-mode upstream detection and the resistance to reflection crosstalk are essential. However, Manchester coding features doubled bandwidth compared with NRZ signal as shown in Fig. 3, imposing new challenge for higher data rate (say 10 Gb/s or even higher) operation.

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References