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Advanced modulation formats for delivery of heterogeneous wired and wireless access networks

C.W. Chow [a,*], C.H. Yeh [b]

[a] Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan
[b] Information and Communications Research Laboratories, Industrial Technology Research Institute, Chutung, Hsinchu 31040, Taiwan

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ABSTRACT

It is believed that the integration of wired and wireless access networks (or heterogeneous network) will provide high bandwidth and flexibility for both fixed and mobile users in a single and cost-effective platform. Here, we propose and demonstrate a signal remodulated wired and wireless network with wireless signal broadcast. Dark-return-to-zero (DRZ) and polarization-shift-keying (PolSK) signals are used for the downstream wired and wireless applications respectively. At the remote antenna unit (RAU), the PolSK signal is demodulated to produce the binary-phase-shift-keying (BPSK) signal, which will be used for the wireless broadcast application. Signal remodulation is demonstrated using reflective semiconductor optical amplifier (RSOA) as a colorless reflective modulator in the optical networking unit (ONU)/RAU. The downstream signal is remodulated at the ONU/RAU to produce the non-return-to-zero (NRZ) upstream signal.

1. Introduction

A strong upgrade of existing access network is needed in order to cope with the exponential increase of bandwidth demand. These networks should provide bi-directionality, flexibility and lower cost per customer. Today's wired access networks [1–3] based on fiber to the home (FTTH) and time division multiplexed (TDM) based passive optical network (PON) technologies provide high bandwidth to users but are not flexible enough to allow roaming connections. They also need massive fiber deployment to reach end-users. On the other hand, wireless networks offer mobility to users, but do not have high enough bandwidth to allow high definition television (HDTV) distribution and interactive multimedia applications. Because of this, integration of wired and wireless services for future access networks will lead to convergence of the high bandwidth for both mobile and fixed end-users in a single and cost-effective platform. This can be implemented by using radio-over-fiber (ROF) systems and wavelength division multiplexed passive optical network (WDM-PON) to provide wireless and wired applications, respectively.

In the future, high frequency carriers ($\geqslant$60 GHz) will be required to carry high data rate wireless signals. However, the cell sizes are limited due to the high atmospheric losses in these high frequency bands. While this is good for efficient spectral utilization for in-building wireless applications, it also means that a large number of antennas and an extensive distribution fiber network are required for wireless network. Because of this, colorless remote antenna unit (RAU) with centralized optical carrier distribution [4,5] could be a promising cost-effective candidate. Previously proposed wired/wireless networks require precise optical filtering [6], or complex modulator structure [7] or costly light source [8]. Here, we demonstrate a signal remodulated wired and wireless access network using a Mach–Zehnder modulator (MZM) and a phase modulator (PM) at the head-end (HE) to generate the required two data channels. Upstream signal remodulation is also demonstrated. Hence, expensive tunable laser source inside the optical networking unit (ONU)/RAU is not required. Cost can be further reduced by wavelength reuse. Reflective semiconductor optical amplifier (RSOA) is used as a colorless modulator in the ONU/RAU. Dark-return-to-zero (DRZ) and polarization-shift-keying (PolSK) signals are transmitted from the HE. At the ONU/RAU, the PolSK signal will be demodulated to binary-phase-shift-keying (BPSK) signal for the wireless broadcast application. The DRZ signal will be serve for PON application. The downstream signal will be remodulated to produce the upstream non-return-to-zero (NRZ) on–off keying (OOK) signal. PolSK is regarded as one of the promising modulation formats for future optical networks [9,10]. 40-Gb/s PolSK transceiver [11] has been demonstrated and available recently. Pre-coding and decoding are not required when compared with differential phase shift keying (DPSK) signal, which is also

* Corresponding author. Address: Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Rm 235A, Tin Ka Ping Building, Hsinchu 30010, Taiwan. Tel.: +886 3 5712121x56334.
E-mail address: cwchow@faculty.nctu.edu.tw (C.W. Chow).

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considered as another advanced modulation format in future optical networks.

2. Architecture and experiment

Fig. 1a shows the proposed architecture of the heterogeneous wired and wireless network. A single-drive MZM is used for DRZ (first channel) generation. The DRZ is used for wired PON application. The MZM is electrically driven by a differentially precoded 10 Gb/s NRZ data (D'_1, where " ′ " means differentially encoded) with an amplitude of $2V_\pi$. The MZM is biased at the minimum of the transmission curve. When the applied electrical NRZ drive voltage is sweeping from high-to-low or low-to-high, the output optical state of the MZM will be changing from a maximum, through a minimum, to an adjacent maximum, so produced a dark optical pulse as shown in Fig. 1b. This is like the DPSK modulation generation by a MZM. The PM is used for the second channel modulation. In order to generate the PolSK signal, an input optical signal will be launched at an angle with respect to the transverse-electric (TE) axis of a $LiNbO_3$ phase modulation (PM). The anisotropy of the electro-optic coefficient of $LiNbO_3$ crystal allows the relative phase shift between the two optical axes (TE and transverse-magnetic (TM)) to change as a function of applied voltage. Hence, the phase shift between the two axes modulates the output polarization, producing a PolSK signal at the output of the PM.

In order to encode the PolSK signal into the DRZ signal, the polarization of the CW launched into the MZM is adjusted so that the TE polarization signal is encoded in DRZ and the TM signal is un-modulated. The continuous wave (CW) source is a distributed feedback laser (DFB) at 1548 nm in the experiment. Then it is launched into the PM for PolSK modulation. The phase information between the dark pulses in the TE polarization of the first channel should be removed to encode the second channel (PolSK). We can rewrite the phase information onto the optical signal between the dark pulses by applying a 10 Gb/s, $D'_1 \oplus D_2$ electrical data to the PM. "$\oplus$" is the exclusive-OR (XOR) logic operation implemented using external electric circuit. By using the identities: $D'_1 \oplus D'_1{=}0$, and $0 \oplus D_2 = D_2$, the phase information between the DRZ pulses can be removed and re-phased to D_2 in the phase of the TE polarization after passing through the PM. We need to control the time alignment between the two data channels, so that the data is applied to the optical signal between the dark pulses. Hence, at the output of the HE, the downstream signal carrying DRZ and PolSK is generated, as shown in Fig. 1c.

The signal is transmitted through the feeder fiber to the ONU/RAU via a pair of Gaussian shaped arrayed waveguide gratings (AWGs), have 50 GHz bandwidth. The signal is then propagating through 20 km of feeder single mode fiber (SMF) with dispersion parameter of 17 ps/nm/km. Using two transmission fibers is to reduce Rayleigh backscattering; however it will increase the cost of

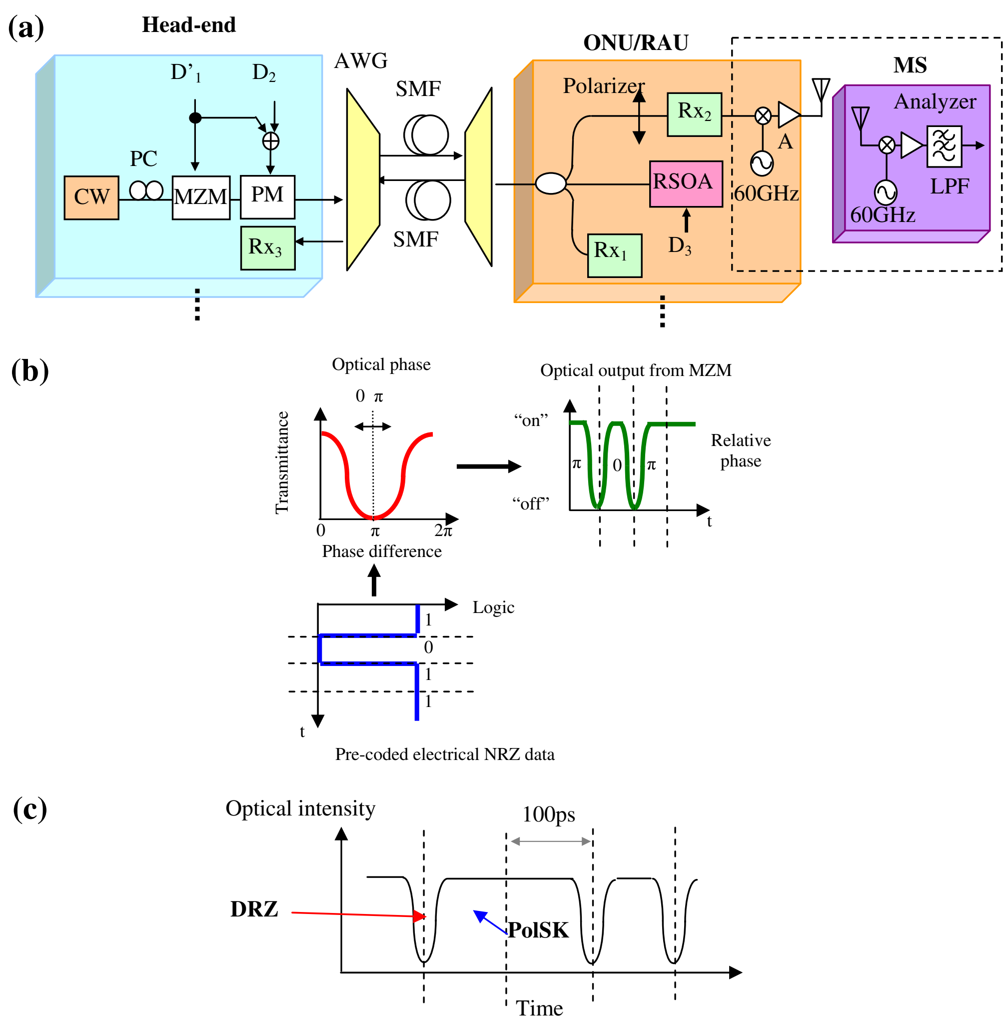

Fig. 1. Architecture of the proposed wired and wireless network. MZM: Mach–Zehnder modulator, PM: phase modulator, SMF: single mode fiber, AWG: arrayed waveguide grating, LPF: low pass filter, A: RF amplifier, RAU: remote antenna unit, MS: mobile station. (b) Operation of the MZM to generate DRZ signal. (c) Schematic time trace of the downstream signal carrying DRZ and PolSK.

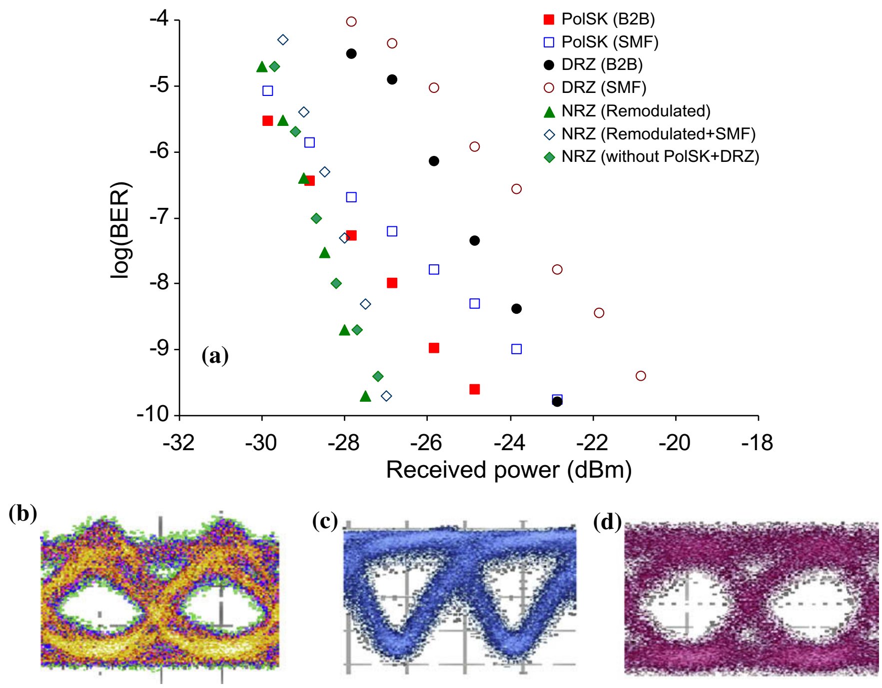

Fig. 2. (a) BER measurements. Eye diagrams of (b) 10 Gb/s demodulated PolSK (at Rx_2), (c) 10 Gb/s DRZ (at Rx_1), and (d) remodulated 2.5 Gb/s OOK (at Rx_3) after transmission.

the network. For the detection of DRZ signal (D_1), 10% the optical power is launched into a 10 GHz optically pre-amplified Rx_1. Another 10% of the downstream signal is launched to a polarizer (for PolSK demodulation (D_2)) and received by a 10 GHz optically pre-amplified ac-coupled Rx_2. At the output of the Rx_2, the NRZ data (D_2) is up-converted (mixed with a 60 GHz electrical sinusoidal signal) for wireless broadcast application. The remaining of the downstream signal is launched into the RSOA for signal remodulation. The RSOA has a small signal gain of 20 dB, peak wavelength at 1550 nm, 10-dB gain bandwidth from 1510 nm to 1580 nm (90 mA bias current), polarization dependent gain of ~1 dB, noise figure of 7 dB, saturated output power of ~2 dBm, electrical modulation bandwidth of 2.5 GHz. It is driven by a 2.5 Gb/s NRZ data at PRBS $2^{31}-1$ to produce the upstream signal. The RSOA was dc-biased at 85 mA via a bias-T. The upstream signal is detected by a 2.5 GHz optically pre-amplified Rx_3 at the HE. Due to the unavailability of 60 GHz source at the laboratory, simulations using VPI Transmission Maker V7.5 were performed (dashed box in Fig. 1a). A BPSK signal (10 Gb/s data on 60 GHz carrier) will be obtained at the output of the mixer and emitted via the antenna. At the mobile station (MS), the RF signal will then be down-converted and analyzed.

3. Results

Fig. 2a shows the bit-error rate (BER) measurements of the downstream and upstream signals at back-to-back (B2B) and after SMF transmission, with the corresponding eye diagrams after the transmission. Error free operations are observed in each case with clear open eyes. We measured about 2 dB power penalties in the downstream PolSK (at Rx_2) and DRZ (at Rx_1) signals, respectively. Chromatic dispersion introduces power penalties to the PolSK and DRZ signals. We measured that the polarization–offset tolerance at 1-dB penalty window is about 16°. In practice, since the random birefringence of buried optical fiber networks typically causes only 2–10° fluctuations in the polarization angles of the propagating signals [12], a slow dynamic polarization control may be used to compensate the polarization fluctuation [13].

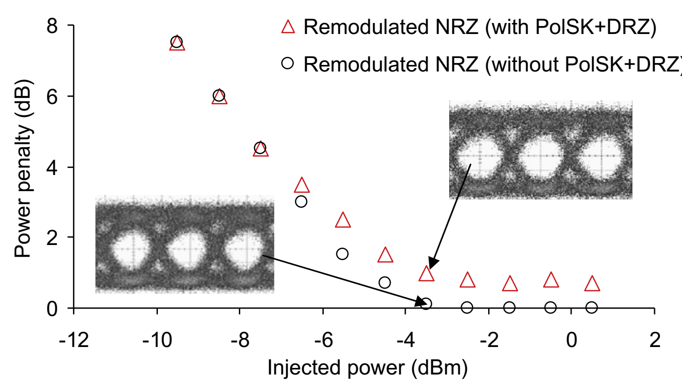

Fig. 3. BER of the upstream NRZ signal against the injected powers into the RSOA with and without the PolSK + DRZ signals.

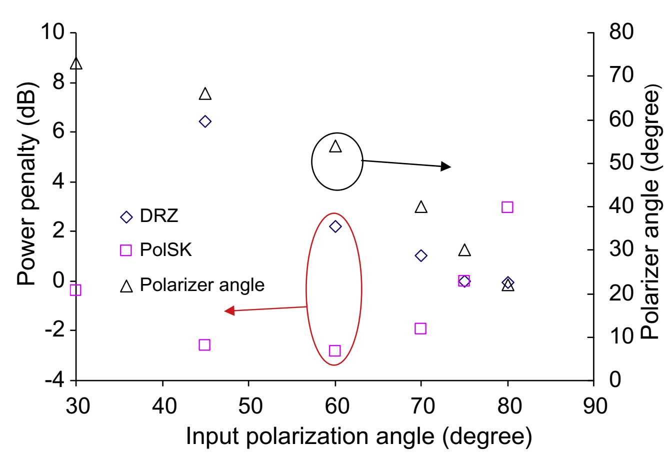

Fig. 4. Power penalties generated in the DRZ and PolSK signals at different launching angles at the HE, and the polarization angle for the PolSK demodulation.

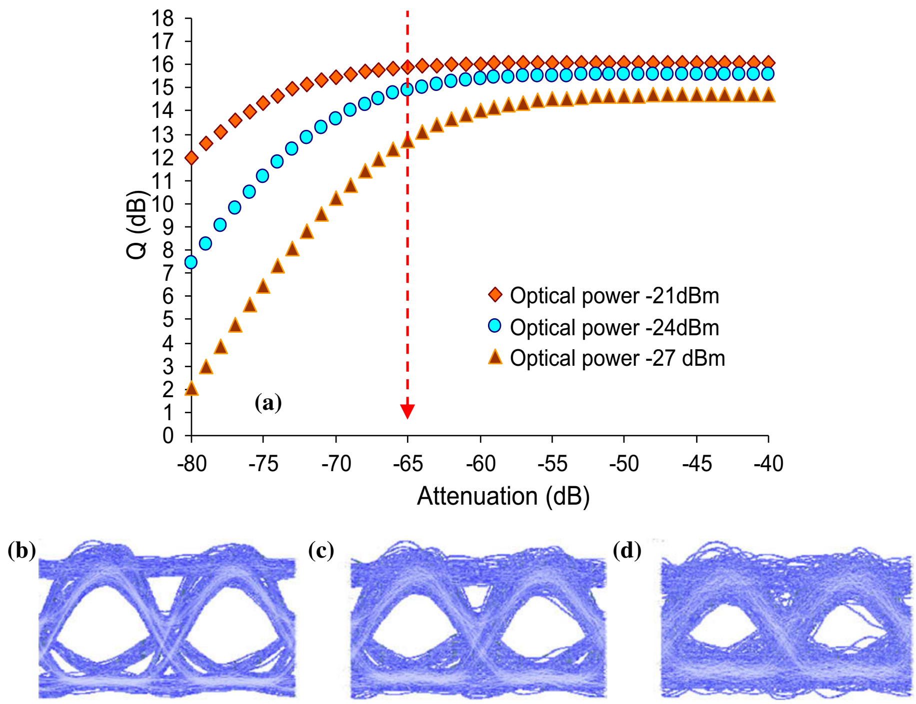

Fig. 5. (a) Simulated Q (dB) of the down-converted BPSK signal at the MS under different attenuations between the RAU and the MS. Simulated eye diagrams of the down-converted BPSK signal inside the MS at 65 dB attenuation, when input optical power to Rx_2 is (b) −21 dBm, (c) −24 dBm and (d) −27 dBm.

Due to the high residual optical background between the DRZ pulses, higher Rx sensitivity of DRZ signal when compared with PolSK and NRZ signals is observed. About 1 dB power penalty is measured in the upstream remodulated NRZ signal (at Rx_3). Fig. 3 shows the BER of the NRZ signal against the injected powers into the RSOA with and without the PolSK + DRZ signals. The remodulated NRZ signal performs slightly better when the downstream PolSK and DRZ signals are switched off due to the polarization dependent gain of the RSOA.

Ideally, in order to produce a PolSK signal, the launched angle to the PM is 45°. The can produce the optimum phase shift to the TE polarization of the signal with respect to the TM polarization, resulting in the highest modulation index of the PolSK signal. However, launching at 45° will result in low modulation index of the DRZ signal. We studied the power penalties generated in the DRZ and demodulated PolSK signals at different launching angles inside the HE. Fig. 4 shows the power penalties of the DRZ and PolSK signals at different input polarization angles to the MZM at the HE. 0° input polarization represents the input signal was launched at TM polarization of the MZM. As described before, the PolSK signal has the lowest power penalty at ~45°. However, the modulation index of the DRZ signal is too low and a high power penalty of 6 dB is observed due to the reduced extinction ratio of the DRZ signal. By offsetting the input polarization towards the TE polarization (towards 90° input polarization), higher optical power will be launched to the TE polarization. Hence, the extinction ratio of the DRZ signal increases; and lower power penalty is observed. In Fig. 4, we can observe that the intercepting point of the input polarization is at 75°. It is also worth to mention that by adjusting the input polarization angles, the polarizer at Rx_2 for the PolSK demodulation should also be changed accordingly to obtain the best receiver sensitivity at each case. Fig. 4 also shows the polarization angle for the PolSK demodulation.

We also performed numerical simulations (due to the unavailable of the 60 GHz electrical source in the laboratory) for the BPSK (10 Gb/s data on 60 GHz carrier) signal. Three different optical launched powers to the Rx_2 inside the RAU (−27 dBm, −24 dBm, −21 dBm) were studied. −24 dBm launched power is selected due to the error-free demodulated PolSK condition as shown in Fig. 2. Inside the RAU and MS, radio frequency (RF) amplifiers (A) (20 dB gain, noise Fig. 3 dB) were used. In the simulation analysis, in order to emulate the air loss between the RAU and MS; the antennas are removed and a RF attenuator is used to connect the RAU and MS. In real situation, the attenuation due to atmospheric gases for a standard atmosphere at 60 GHz band is 10–20 dB/km [14]. Fig. 5 shows the Q (dB) of the down-converted BPSK signal received at the MS under different attenuations, with the corresponding simulated eye diagrams of the down-converted BPSK signal inside the MS at 65 dB attenuation, when input optical power to Rx_2 is −21 dBm, −24 dBm and −27 dBm, respectively. The results show that the atmospheric attenuation can up to 65 dB when the optical input power to the RAU is −24 dBm. We can also observe that the rate of degradation of the Q-value is much faster when the input optical power to the Rx_2 inside the RAU is small. This implies that launching higher input power to the Rx_2 is important.

4. Conclusion

We proposed and demonstrated a heterogeneous wired and wireless access network using RSOA as colorless modulator having the wireless signal broadcast capability. 10 Gb/s DRZ and 10 Gb/s BPSK signals were used for the downstream PON application and wireless broadcast respectively. Signal remodulation by wavelength reuse has also been demonstrated, generating the upstream 2.5 Gb/s NRZ signal from the downstream signal. Numerical simulations for the BPSK (10 Gb/s data on 60 GHz carrier) signal were also performed, showing that the atmospheric attenuation can up to 65 dB when the optical input power to the RAU was −24 dBm. The rate of Q-value degradation is much higher when the input optical power to the Rx_2 inside the RAU is small. Hence launching higher input power to the Rx_2 is important.

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