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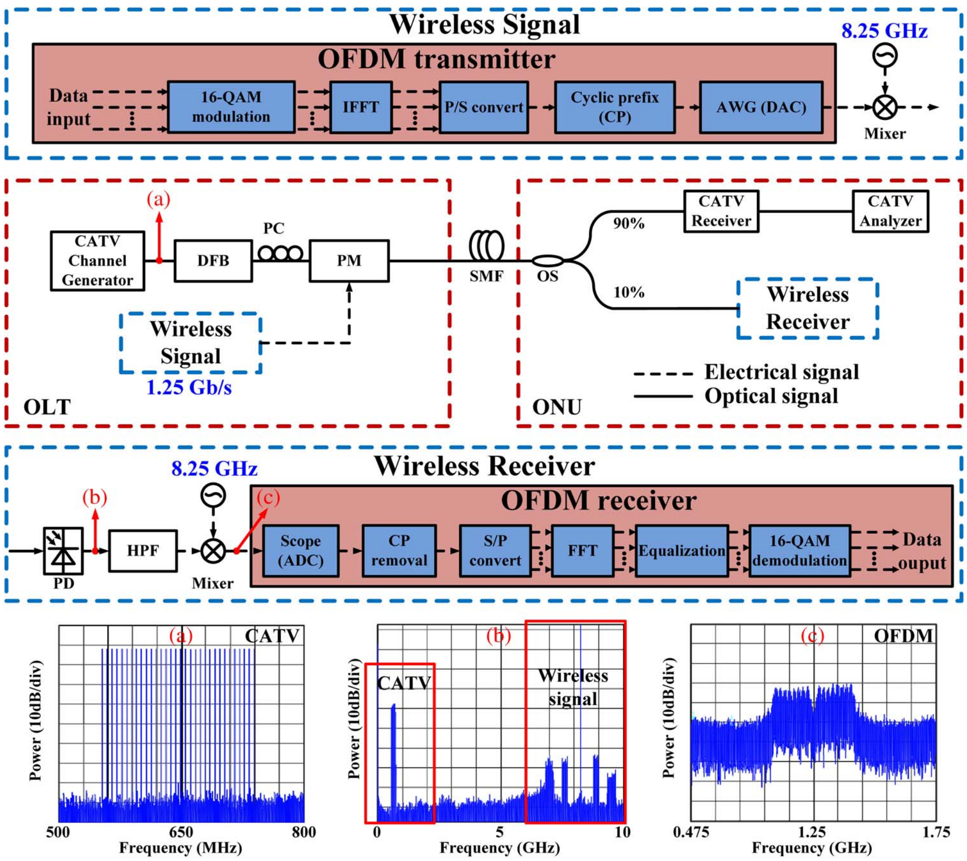

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Multi-Service Cable Television System Using a Single Wavelength

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Abstract: This paper presents a multi-service cable television (CATV) system using a single wavelength. The multi-service CATV systems can transmit both CATV and wireless signals by using one external modulator on a single wavelength over a single fiber. Moreover, this multi-service transport system, in contrast to the previously developed systems, does not incur the dc bias drift problem. In addition to satisfying the CATV requirements where excellent performances of carrier-to-noise ratio (CNR), composite second-order (CSO), and composite triple beat (CTB) are achieved for CATV signals, the multi-service transport system also satisfies the demand for high-quality wireless signal transmission over a 25-km single-mode fiber (SMF).

Index Terms: Cable television, multi-service transport system.

1. Introduction

Fiber-Optical CATV systems play an integral part in distribution infrastructure, owing to their broad bandwidths and longer reach properties to provide high quality video signals to subscribers [1], [2]. Additionally, to satisfy the tremendous demand of handheld devices, radio over fiber (ROF) technique which integrates the advantages of both optical and wireless communications is highly promising for satisfying such requirements as well [3]–[9]. As a result, fiber-optical CATV in combination with ROF technology has received growing interest, owing to its ability to provide both wireline and wireless connectivity in a cost-effective structure [10], [11]. To achieve this objective, a hybrid network structure in [12], [13] is developed to use an external intensity modulator to generate wireline and wireless signals simultaneously. Despite the directness and simplicity of this combining scheme, the wireless signal in that scheme is modulated in the nonlinear region due to the existence of the wireline signal. Therefore, nonlinearity of the external modulator and interchannel interference between wireline and wireless signals will significantly limit the overall transmission performance. To overcome the draw-back, two laser sources and two optical ultra-narrow band filters are deployed in the [10] to individually service the CATV and wireless signals transmissions through a common trunk fiber. However, the cost of deploying multiple laser diodes and optical ultra-narrow band filters in that system will significantly limit its applications. Instead, the optical carriers in the [11] are generated by a single distributed feedback laser (DFB) diode and then utilizing three optical ultra-narrow band filters and external intensity modulator to select and modulate the downstream signals with three individual optical carriers. In this case, a single DFB could be utilized to service multiple downstream transmissions with lower maintenance cost. However, using three optical ultra-narrow band filters to select the appropriate wavelength will increase the real deployment cost. Additionally, the external intensity modulator may incur a direct current bias-drifting problem in which will reduce the system robustness.

This work presents a novel multi-service CATV system by using a phase modulator (PM) on a single wavelength. In contrast with optical intensity modulator schemes [11]–[13], the PM system does not incur the dc bias-drifting problem and can provide a relatively steady optical power, which withstand fiber nonlinearities that are self-phase-modulation (SPM), cross-phase-modulation (XPM) and cross-gain-modulation (XGM) [14], [15].

Generally, the PM signal with its constant optical power envelope cannot be detected directly by a photodetector (PD). An optical phase to intensity converter is required to be inserted ahead the PD. In order to simplify the transport system, the optical phase to intensity converter is replaced by the deployed SMF between the transmitter and the receiver. Experimental results demonstrate that the phase-modulated wireless signal is easily converted into an intensity-modulated signal and can be detected along with the intensity-modulated CATV signal after 25 km SMF transmission. Excellent performances of CNR, CSO, and CTB are achieved for CATV applications, along with high-quality wireless signal transmission achieved as well.

2. Experimental Setup

Fig. 1 shows the setup of the multi-service CATV transport system using a single wavelength. To simulate multi-carrier CATV signals, 32 NTSC-channels (553.25-739.25 MHz) are generated using a Matrix SX-16 signal generator, as shown in Fig. 1(a). The CATV signals are measured by a CATV analyzer (HP 8591C CATV analyzer). A 1.25 Gbps 16 quadrature amplitude modulation (QAM) orthogonal frequency-division multiplexing (OFDM) signal is generated using an arbitrary waveform generator (Tektronix AWG7102). The sampling rate and digital-to-analog converter resolution of the DAC are 10 GS/s and 8 bit, respectively. OFDM is a promising technology [16], [17], owing to its extremely high spectrum efficiency and robust dispersion tolerance to improve the transmission performance and capabilities of ROF systems [18], [19]. Moreover, the proposed multi-service CATV system is evaluated by up-converting the OFDM signal to RF range via mixing with a 8.25 GHz sinusoidal signal. In the optical line terminal (OLT), the CATV signal is directly modulating with the DFB laser diode. The DFB laser diode is a commercial device (NTT Electronics Corporation) with a threshold current of 20 mA and is biased at 75 mA. Subsequently, the generated optical CATV signal is launched into the phase modulator and is re-modulated with the up-converted 1.25 Gbps/8.25 GHz 16 QAM OFDM signal before been fed into a span of 25 km SMF. The modulation index of phase modulator is about 0.5 $V\pi$. Moreover, the phase modulator is manufactured by EOSPACE Inc. The optical insertion loss and electrical bandwidth of phase modulator are about 2.4 dB and 20 GHz, respectively. The inset of the Fig. 1 schematically depicts the OFDM transmitter, which consists of parallel-to-serial conversion, quadrature amplitude modulation, inverse fast Fourier transform (IFFT), cyclic prefix (CP) insertion, and digital-to-analog conversion (DAC). The IFFT size is 512. Notably a 1.25 Gbps 16 QAM OFDM signal with 16 subcarriers and occupying a total bandwidth of 312.5 MHz can be generated.

When the downstream lightwave arrive the optical network unit (ONU), its power energy is split by a 1×2 optical splitter (OS) with splitting ratio of 90/10 where its two output ports are individually connected to a CATV receiver and a wireless receiver. The optical wireless signal is amplified using an optical amplifier, filtered by an optical bandpass filter to eliminate amplified spontaneous emission noise; is attenuated by a variable optical attenuator. Fig. 1(b) schematically depicts the wireless receiver, in which the optical signal is detected by a 12.5 GHz broadband PD. The received signal is then filtered by an electrical high-pass filter to remove the CATV signal. Fig. 1(c) shows the electrical spectrum of the 16 QAM OFDM signal. The 16 QAM OFDM signal is then down-converted to baseband and captured by a real-time scope with a 20 GS/s sampling rate and a 3 dB bandwidth of 4 GHz. The transmission performance of the 16 QAM OFDM signal is analyzed using an off-line Matlab digital signal processing program.

This work also attempts to confirm the role of SMF in dispersive devices in order to achieve phase modulation-intensity modulation conversion by determining the frequency response with 25 km

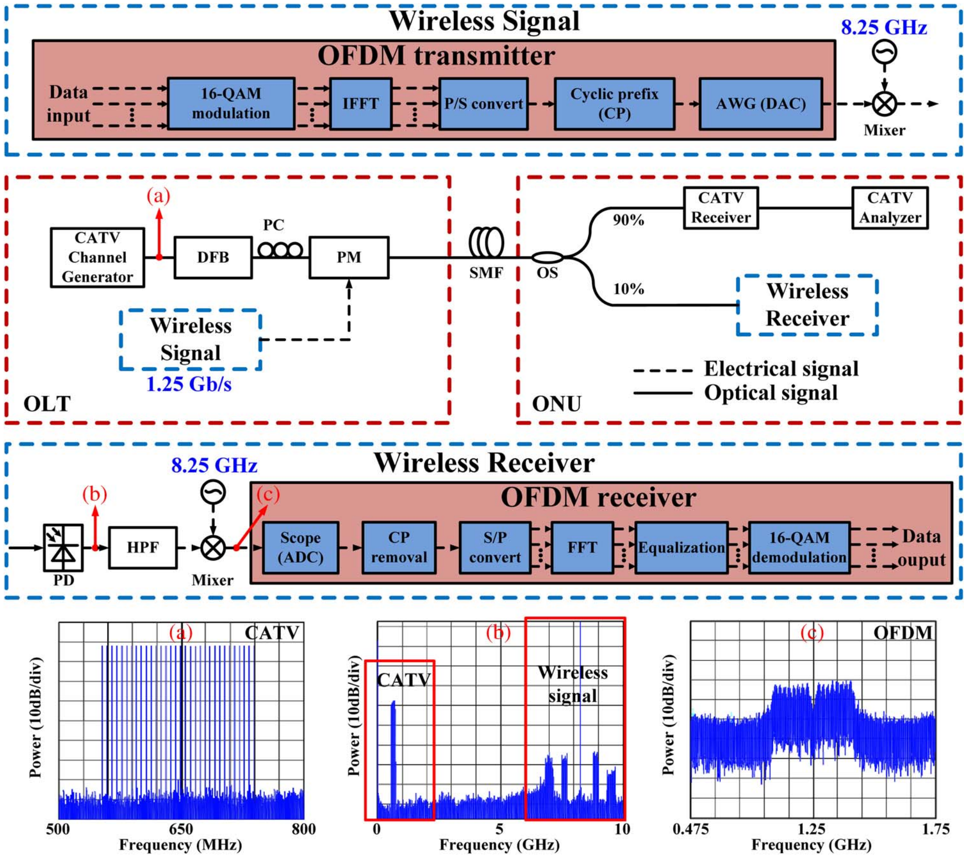

Fig. 1. Multi-service CATV transport system based on a phase modulator. (DFB: distributed feedback laser, PC: polarization controller, PM: phase modulator, SMF: single-mode fiber, OS: optical splitter, IFFT: inverse fast Fourier transform, DAC: digital-analog converter, PD: photodetector, HPF: high-pass filter, ADC: analog-digital converter, FFT: fast Fourier transform).

SMF, via a network analyzer, as shown in Fig. 2. Theoretical results can be written as [15]

$$H(\omega_m) \propto \cos\left(\frac{\pi D \lambda_0^2 f_m^2}{c} + \frac{\pi}{2}\right) \tag{1}$$

where the first term on the right side denotes the dispersion-based phase modulation-intensity modulation conversion; c represents the optical wave propagation velocity in free space; D refers to the accumulated dispersion of the SMF link; λ_0 denotes the wavelength of the optical carrier; and f_m represents the modulating signal frequency. The lower and higher -10 dB cutoff frequencies are 4.7, 16.3 and 18.3 GHz, respectively, which optimally exploit the allowable bandwidth about 4.7 to 16.3 GHz. Based on the transfer function of (1), a simulation frequency response correlates well with the experimental results.

3. Experimental Results and Discussion

Figs. 3–5 schematically depict the CNR, CSO and CTB definitions as well as the corresponding performances under various CATV channels, respectively. In fiber-optical CATV transport systems, a higher optical power is received implies a more improved CNR performance. The theoretical expression of CNR is as follows [20]:

$$CNR = \left(CNR_{\mathrm{RIN}}^{-1} + \left(CNR_{\mathrm{th}}^{-1} + CNR_{\mathrm{shot}}^{-1}\right)\right)^{-1}, \tag{2}$$

$$CNR(dB) = -10\log\left[10^{-\frac{CNR_{\mathrm{RIN}}}{10}} + 10^{-\frac{CNR_{\mathrm{th}}}{10}} + 10^{-\frac{CNR_{\mathrm{shot}}}{10}}\right], \tag{3}$$

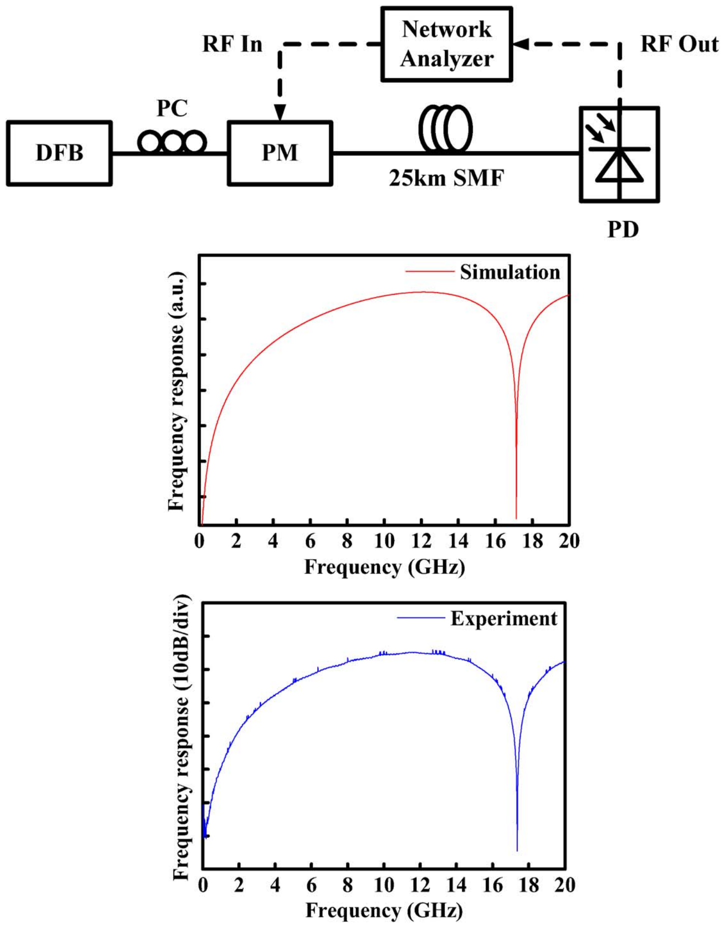

Fig. 2. Architecture and frequency responses of the phase modulation to intensity modulation conversion using 25km SMF (DFB: distributed feedback laser, PC: polarization controller, PM: phase modulator, SMF: single-mode fiber, PD: photo detector).

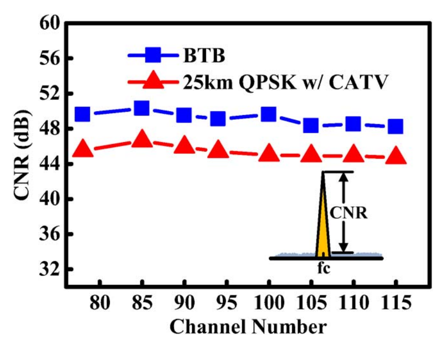

Fig. 3. Measured CNR values under various CATV channels, as well as the schematic diagrams of the CNR definition.

where each CNR term corresponds to a different element of the transmission system: Notably, CNR_{RIN} originates from the laser diode relative intensity noise, and CNR_{th} and CNR_{shot} are associated with the optical receiver. According to the insert of the Fig. 3, the CNR value in each visual carrier, f_c, should exceed 43 dB at consumer premises; otherwise, "snow" phenomenon occurs in that channel. The measured CNR in various CATV channels always exceeded 43 dB. A

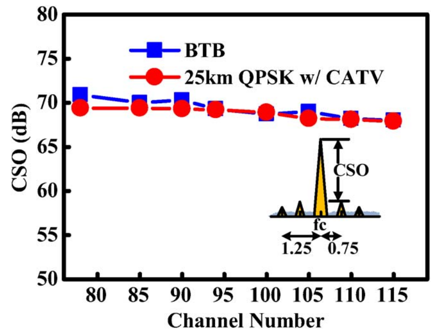

Fig. 4. Measured CSO values under various CATV channels, as well as the schematic diagrams of the CSO definition.

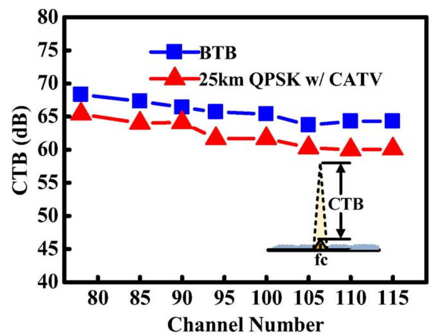

Fig. 5. Measured CTB values under various CATV channels, as well as the schematic diagrams of the CTB definition.

comparison with 0 km transmission measurements shows that a power penalty of about 3.78 dB for the CNR values was presented at the 25 km transmission, due to lower received power. Moreover, a long-distance 1550 nm CATV system that transported 64 QAM signals was demonstrated [21]. This system can achieve a CNR of 30 dB after 740 km SMF transmission for Digital Video Broadcasting-Cable (DVB-C). This proof of our system could also support the DVB-C system [22].

In a standard frequency allocation CATV transport system, when multiple even-spaced channels are transmitted via nonlinear devices, some discrete distortion products are occurred through various combinations of CATV carriers. In the calculation of the CSO performance, the mathematical formula of the CSO is defined as:

$$CSO = 10\log\frac{\text{video carrier level}}{\text{second order beat level}}. \tag{4}$$

Equation (4) and Fig. 4 reveal that a lower power difference among the carrier and the second-order products will imply a poor CATV transmission performance. To ensure acceptable quality of service, the CSO values should exceed 53 dB at the consumer premises. Similarly, the CTB measurement is defined as follows:

$$CTB = 10\log\frac{\text{video carrier level}}{\text{triple order beat level}}. \tag{5}$$

Since some of the triple order distortion products in a CATV system are located at the same frequency of a CATV carrier, the relative RF carrier must be turned on and off when measuring the CTB values. Then, based on the recorded values, the CTB performance can be estimated, which

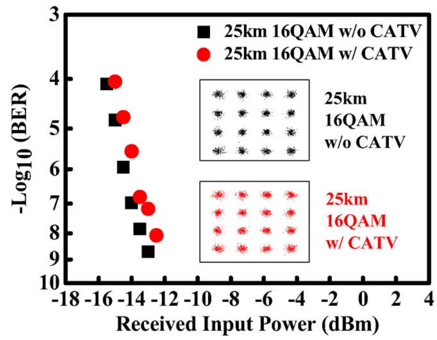

Fig. 6. Measured BER curves and constellation diagrams for the 1.25Gbps 16 QAM OFDM.

must exceed 53 dB at the client premise. Figs. 3–5 clearly indicate that the measured CNR, CSO and CTB values exceed 45/65/60 dB.

Fig. 6 shows the measured bit error rate (BER) values and constellation diagrams of the downstream 1.25 Gbps 16 QAM OFDM signal when the CATV signals are turn on and off. The power penalty between CATV on and CATV off is less than 1 dB. The constellation diagrams in each case are clear, and high-quality wireless signal transmission is achieved.

4. Conclusion

This work presents a multi-service CATV system that transmits CATV and wireless signal simultaneously by a single wavelength only. A multi-carrier CATV signal is modulated in the amplitude domain of the optical carrier, and 1.25 Gbps 16 QAM OFDM signals are modulated in the optical phase domain. Unlike the published schemes which utilizing an optical phase to intensity converter to convert the optical phase-modulated OFDM signal into an intensity-modulated OFDM signal, the optical PM signal in the proposed system is demodulated by fiber dispersion itself only. Analytical results indicate that a single optical wavelength can serve these two applications simultaneously without serious distortion. This multi-service transport system, in contrast to the previously developed systems does not incur the DC bias drift problem. Furthermore, modulating these two signals at different domains can prevent inter-channel interference. Excellent CNR, CSO, CTB and BER performance are experimentally achieved for the CATV and high-quality wireless signal transmissions.

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