Hybrid CATV/16-QAM OFDM in-building networks over SMF and GI-POF transport

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Abstract: A hybrid CATV/16-QAM OFDM in-building network over a combination of single-mode fiber (SMF) and graded-index plastic optical fiber (GI-POF) transport is proposed and experimentally demonstrated with good qualities of service. In this system, a 1556 nm optical signal is directly transmitted along with two fiber spans (20-km SMF + 25-m GI-POF). Without using any wavelength conversion or bridge circuit between SMF and POF connection, error free transmissions with sufficient low bit error rate (BER) values are achieved for 2.5Gbps/2.5GHz and 5Gbps/2.5GHz OFDM signals; as well as good performances of carrier-to-noise ratio (CNR), composite second-order (CSO), and composite triple beat (CTB) are obtained for CATV one. This proposed network reveals an outstanding one with economy and convenience to be installed.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.1155) All-optical networks; (060.2360) Fiber optics links and subsystems.

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1. Introduction

Fiber optical communication systems have been deployed widely with high expectations to provide broadband integrated services. Optical fiber with its high capacity, low attenuation, light weight and electromagnetic noise interference (EMI) free characteristics offers an ideal pathway to distribute signals [1–3]. Nevertheless, fiber optical communication systems for last mile end user applications have not yet addressed. With the rapid development of communication technologies, the increasing requirements raise the needs for high-speed and high bandwidth, not only for the single-mode fiber (SMF)-based backbone networks, but also for the plastic optical fiber (POF)-based in-building ones. SMF, in particular, has already established an undisputable position to distribute high quality signals. As a widespread medium, SMF offers better performances than POF in terms of attenuation and dispersion et al. However, when the SMF is deployed toward intra-house networks, installation cost and convenience are beyond disputed issues needed to be solved. The SMF with relative much smaller core size requires trained persons, high precision devices, and higher cost to install and maintain. POF alternatively has much larger core size, relative smaller bending radius, and easier to be installed characteristics. In result, the in-building connection becomes a critical bottleneck to successfully deliver high quality signals from the central office/head-end to the home. To overcome the challenge, a new kind of in-building network medium is required. Recently, graded-index POF (GI-POF) has been developed with excellent optical characteristics [4]. This flash product is the potential candidate to solve the problem of last mile end user. Clear advantages are offered by using the GI-POF for in-building networks: its large core diameter and small bending radius considerably eases coupling and splicing, as well as its ductility and flexibility simplifies installation in customer locations [5–7]. As a result, GI-POF is an ideal medium to integrate fiber backbone networks and in-building ones. The feasibility of transmitting analog CATV signals over a combination of SMF and GI-POF links was demonstrated previously [8]. However, the architecture of systems can be further improved to achieve both CATV and wireless signals to the home device applications. The transmitted signals can be further integrated by delivering both analog CATV and digital 16-quadrature amplitude modulation (QAM) orthogonal frequency-division multiplexing (OFDM) signals simultaneously. OFDM is a promising technology which has very high spectrum efficiency and robust dispersion tolerance to improve the transmission performances and capabilities of systems [9–11]. Comparing with utilizing on-off keying (OOK) data format, employing 16-QAM OFDM signal for example can boost up the spectrum efficiency by four times and can relax the system dispersion effect by a longer symbol period. Additionally, OFDM signal is not a kind of baseband signal, so it is possible to be transmitted simultaneously with the CATV signal. In this paper, a hybrid CATV/16-QAM OFDM in-building network over a combination of SMF and GI-POF transport is proposed and experimentally demonstrated basing on a single optical carrier. Error free transmissions with sufficient low bit error rate (BER) values are achieved for 2.5Gbps/2.5GHz and 5Gbps/2.5GHz OFDM signals; as well as good performances of carrier-to-noise ratio (CNR), composite second-order (CSO), and composite triple beat (CTB) are obtained for CATV one. This proposed network is shown to be a prominent one not only presents its economy in last mile end user application but also reveals its convenience to be installed.

2. Experimental setup

The experimental configuration of our proposed hybrid CATV/16-QAM OFDM in-building networks over a combination of 20-km SMF and 25-m GI-POF links is illustrated in Fig. 1. A total of 77 carriers, from a multiple signal generator (Matrix SX-16), are used to simulate analog CATV channels (channel 2-78). Two 16-QAM OFDM signals (2.5Gbps/2.5GHz and 5Gbps/2.5GHz) are generated offline by MATLAB program and uploaded into a Tektronix arbitrary waveform generator (AWG). The 16-QAM OFDM signals are represented by 64/128 subcarriers, 512/512 FFT sizes, and 2.5GHz/2.5GHz intermediate frequency (IF),

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respectively. Both CATV and 16-QAM OFDM signals are combined by a 2 × 1 RF coupler and directly fed into a distributed feedback laser diode (DFB LD), with a central wavelength of 1556 nm and a relative intensity noise of −165 dB/Hz. The modulated optical signal is then amplified by an erbium-doped fiber amplifier (EDFA), and filtered out by an optical band-pass filter (OBPF) to suppress the amplified spontaneous emission (ASE) noise. The output power and noise figure of EDFA are ~17 dBm and ~4.5 dB, at an input power of 0 dBm, respectively.

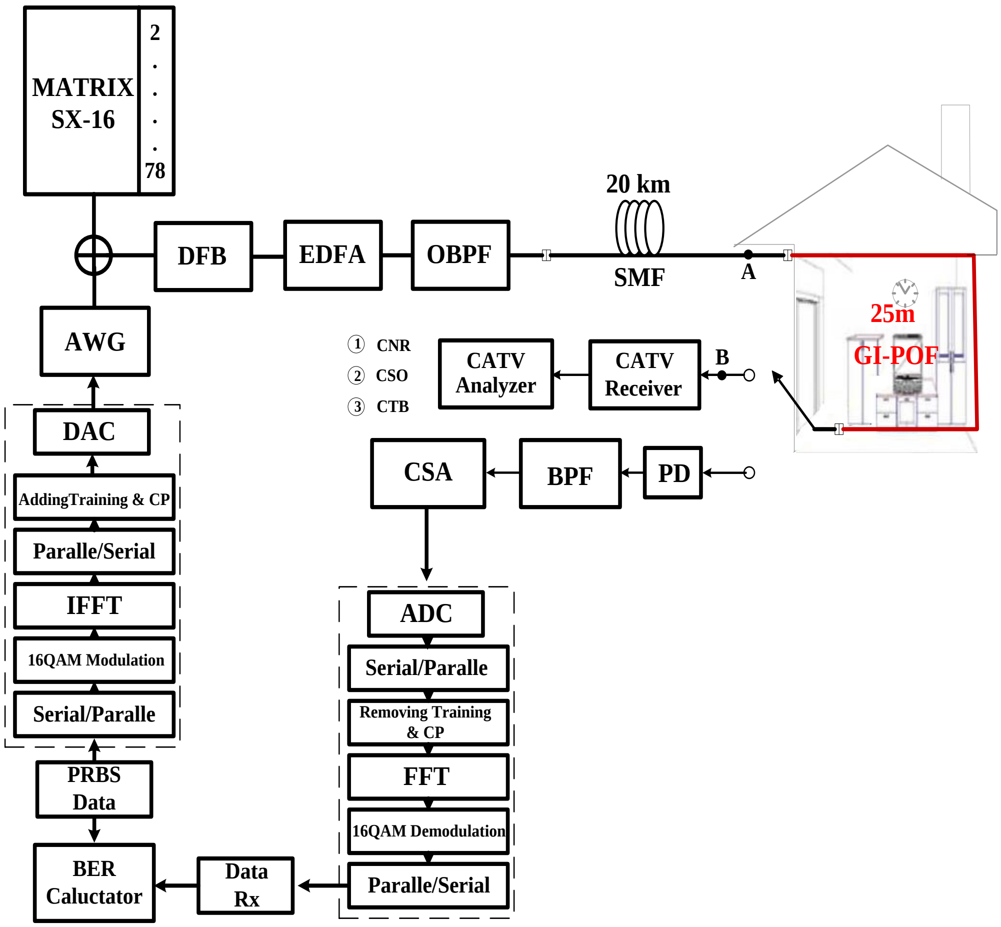

Fig. 1. The experimental configuration of our proposed hybrid CATV/16-QAM OFDM in-building networks over a combination of 20-km SMF and 25-m GI-POF links.

And then, the optical signal is transmitted through two fiber spans: 20 km SMF (with an attenuation of 0.24 dB/km and a dispersion coefficient of 17ps/nm·km) and 25-m GI-POF (Chromis Fiberoptics GigaPOF50SR-PC-SM, with core diameter = 50 ± 5μm, numerical aperture = 0.185 ± 0.015, macro-band loss <0.25 dB for 10 turns on a 25-mm radium quarter circle, and long-term bend radium = 5.0 mm). The bandwidth-length product of the GI-POF has reached 1.1 GHz·km. Over a combination of 20-km SMF and 25-m GI-POF transmission, one half of the optical signal is received by a CATV receiver; as well as the other half is detected by a high-bandwidth photodiode (PD) (with a 3-dB bandwidth of 10 GHz), and passed through a BPF to remove the spurious. The CATV parameters of CNR, CSO and CTB are analyzed by an HP-8591C CATV analyzer. Subsequently, the 16-QAM OFDM signals are captured by a communications signal analyzer (Tektronix CSA7404B), and processed off-line

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with a MATLAB program to evaluate the BER performances and the corresponding constellation maps.

3. Experimental results and discussion

Similar to the known multi-path effects in the wireless communication systems, modal dispersion is the major factor that degrades the transmission performances of in-building networks, in which leading to signal fading and inter-symbol interference (ISI). In result, multiple carriers OFDM scheme, which has robust dispersion tolerance, is employed to mitigate the signal distortions in such networks. Moreover, the amount of modal dispersion in time (ps) is given by [12]:

$$Dispersion_{time} = NA^2 \times \frac{L}{2nc} \tag{1}$$

where NA is the numerical aperture, L is the fiber length, n is the refractive index, and c is the optical velocity. From Eq. (1), it is obvious that longer GI-POF length causes larger modal dispersion and leads to worse transmission performances. However, since the GI-POF length is only 25 m, it indicates that the performance degradation induced by the modal dispersion is limited. Moreover, the bandwidth-length product of the GI-POF is 0.0625 GHz·km (2.5GHz × 0.025km), it meets the bandwidth-length product demand (the maximum bandwidth-length product of the GI-POF has reached 1.1 GHz·km). In case, the length of the GI-POF is increased, optical frequency multiplying has been proposed to solve the modal dispersion problem [13]; but, sophisticated and expensive phase modulator, and periodic optical filter are required. Although the improvement results are limited as direct-detection technique is employed; however, since sophisticated and expensive high-bandwidth RF devices, phase modulator, as well as periodic optical filter are not used, it presents a feasible way with more economic advantages.

Figures 2(a) and 2(b) show the electrical spectral of the combined CATV and 2.5Gbps/2.5GHz 16-QAM OFDM signals for back-to-back (BTB) as well as over a combination of 20-km SMF and 25-m GI-POF transmission cases, respectively. Figures 3(a) and 3(b) present the electrical spectral of the combined CATV and 5Gbps/2.5GHz 16-QAM OFDM signals for the two cases. In order to provide suitable bandwidth utilization efficiency and to prevent signal interference between CATV and QAM OFDM signals, the central frequency of the employed OFDM signal is carefully selected at 2.5GHz. This is because that the required bandwidth of transmitting the 2.5Gbps/2.5GHz or 5Gbps/2.5GHz OFDM signals is 0.625 GHz or 1.25GHz. This means that the lowest frequencies of the 2.5Gbps/2.5GHz and 5Gbps/2.5GHz OFDM signal are 2.1875 GHz (2.5 – 0.625/2 = 2.1875) and 1.875 GHz (2.5 – 1.25/2 = 1.875), respectively. Both of them are far from the highest carrier frequency of CATV signal (550MHz) as well as are away from the highest 2nd harmonic distortion of the CATV signal (1.1GHz). If the central frequency of the transmitted OFDM signal is reduced to a lower value, such as 1.8 GHz, the frequency bands of these two OFDM signals will close to the highest 2nd harmonic distortion of the CATV signal. So they may be seriously interfered by the CATV signal. On the other hand, if the OFDM central frequency is increased to a higher level, such as 3 or 5 GHz, the entire CATV and OFDM signals will occupy a larger bandwidth and reduce the bandwidth utilization efficiency. As a result, the 2.5 GHz is a suitable central frequency for the employed OFDM signals. Although the 3rd and 4th harmonic distortions for 550 MHz are located at 1.65 and 2.2 GHz, in which they are close to the 1.875 and 2.1875 GHz. However, the amplitude of distortion decreases with the increasing of the order number. Thus, the 3rd and 4th harmonic distortions have very small amplitudes, so they will not induce distortions in QAM OFDM band [14]. In case the QAM OFDM signal is replaced by OOK format at the same central frequency, part of the 2.5Gbps/2.5GHz OOK signal will overlap with the CATV signal as the schematic diagram shown in the Fig. 4(a). So the central frequency of the downstream wireless signal needs to be extended to at least 3.05GHz as shown in the Fig. 4(b). Comparing with 2.5Gbps/2.5GHz 16-QAM OFDM signal,

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it is expected that utilized such 2.5Gbps/3.05GHz OOK signal in the system not only has less spectrum efficiency but also has serious interference with the CATV signal.

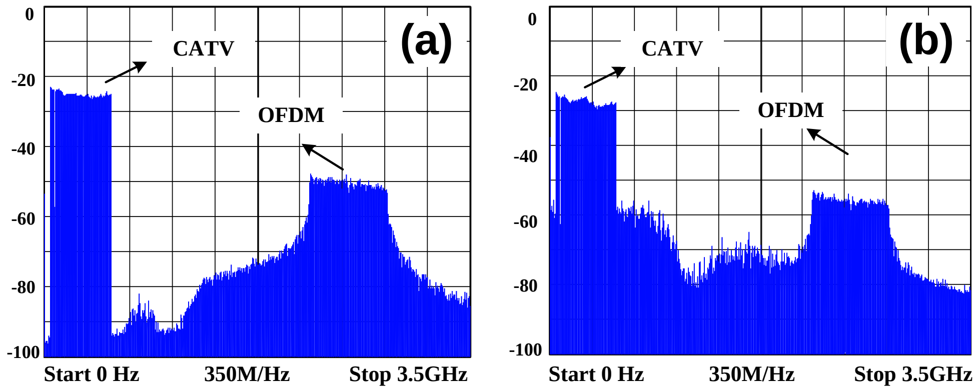

Fig. 2. Electrical spectra of the combined CATV and 2.5Gbps/2.5GHz 16-QAM OFDM signals for (a) BTB case, (b) over a combination of 20-km SMF and 25-m GI-POF transmission case.

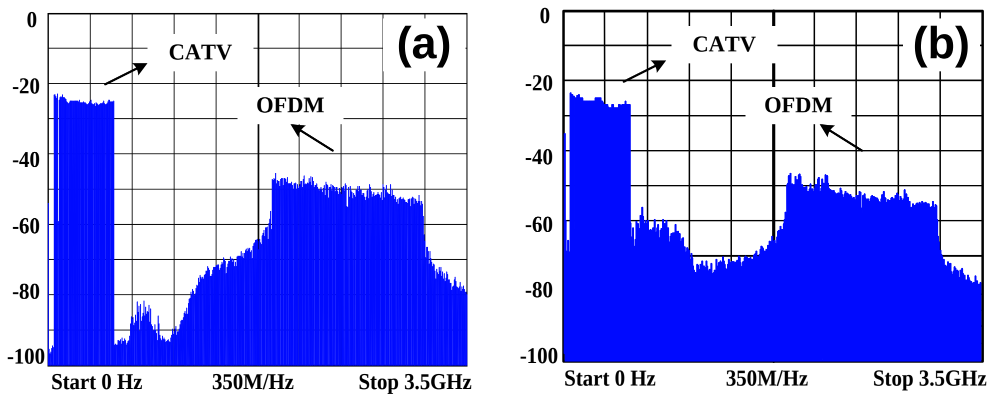

Fig. 3. Electrical spectra of the combined CATV and 5Gbps/2.5GHz 16-QAM OFDM signals for (a) BTB case, (b) over a combination of 20-km SMF and 25-m GI-POF transmission case.

To evaluate the transmitted OFDM signals performances, the measured BER curves and constellation maps are present in Figs. 5(a) and 5(b), respectively. At a BER of 10^{-8}, only a power penalty of 0.7 dB is presented in both 2.5Gbps/2.5GHz cases (Fig. 5(a)). And at a BER of 10^{-6}, a small power penalty of 1 dB is presented in both 5Gbps/2.5GHz ones (Fig. 5(b)). It is obvious that the proposed in-building networks can provide good BER performances and constellation maps, even the OFDM data rate is increased from 2.5 Gbps to 5 Gbps, Error free transmissions are achieved to demonstrate the possibility of establishing a hybrid CATV/16-QAM OFDM in-building network over a combination of 20-km SMF and 25-m GI-POF links. Nevertheless, if the 2.5Gbps/2.5GHz and 5Gbps/2.5GHz OFDM signals are replaced by the 2.5Gbps/3.05GHz and 5Gbps/5.55GHz OOK signals, the relative BER performances are much worse.

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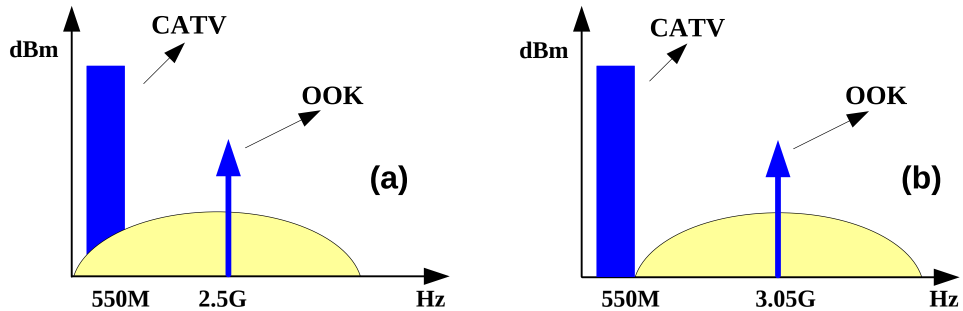

Fig. 4. Schematic spectrum diagram of (a) the 2.5Gbps/2.5GHz OOK signal and the CATV signal, and (b) the 2.5Gbps/3.05GHz OOK signal and the CATV signal.

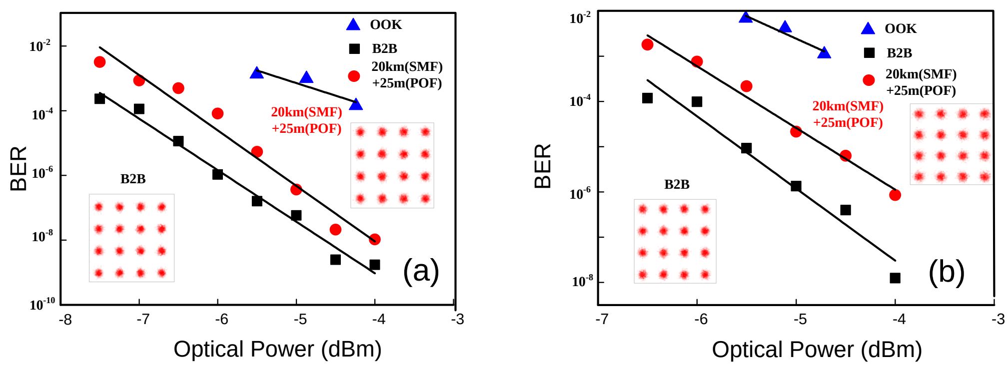

Fig. 5. The measured BER curves and constellation maps for (a) 2.5Gbps/2.5GHz OFDM signal and 2.5Gbps/3.05GHz OOK signal, (b) 5Gbps/2.5GHz OFDM signal and 5Gbps/5.55GHz OOK signal.

Moreover, to find out the impact of 16-QAM OFDM signal and OOK signal on the CATV one, we also measure and evaluate the CATV parameters. The measured CNR, CSO and CTB values are presented in Fig. 6(a) (measured at point A of Fig. 1) and Fig. 6(b) (measured at point B of Fig. 1); as well as Fig. 7(a) (measured at point A of Fig. 1) and Fig. 7(b) (measured at point B of Fig. 1), respectively. For Figs. 6(a) and 6(b), the transmitted signals are CATV and 2.5Gbps/2.5GHz 16-QAM OFDM ones as well as CATV and 2.5Gbps/3.05GHz OOK ones. As to Figs. 7(a) and 7(b), the transmitted signals are CATV and 5Gbps/2.5GHz 16-QAM OFDM ones as well as CATV and 5Gbps/5.55GHz ones. It is clear that the CNR/CSO/CTB values always keep ≥43/53/53 dB under NTSC channel number when the CATV signal is transmitted with the OFDM signal. The measured CNR/CSO/CTB values are roughly 1.2/2/2 dB degraded by power degradations and nonlinear effects of the SMF and POF; however, the measured 43/53/53 dB still satisfies the CATV requirements. No effect of interaction is observed between these two signals due to large carrier frequency separation. Nevertheless, when the OFDM signal is replaced by OOK signal, the overall performance will not satisfy the NTSC standard requirements. In the system, the optical power level at the end of the GI-POF is roughly 0.2 dBm. According to the measured results in the Fig. 5, if a forward error correction (FEC) is employed, the minimum BER requirement for the OFDM signal can be reduced to roughly 10^{-3} [15]. So a roughly 7 dB power budget is reserved for other applications. On the other hand, the core size of our optical CATV receiver is 9 μm which is much smaller than that in the GI-POF. When the optical signal is transmitting through the MMF to the CATV receiver, only a small portion of the optical signal can be received, so a serious 7.5 dB connection loss is presented between the GI-POF and CATV receiver. Fortunately, this loss can be eliminated by utilizing a bigger core receiver. The saved

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power budget can then be used to support additional two or three POF cables directed to different rooms.

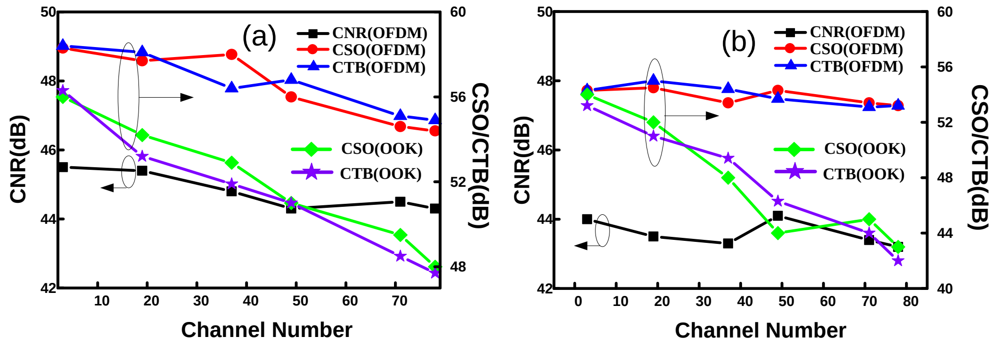

Fig. 6. The measured CNR, CSO and CTB values for transmitting signals of CATV and 2.5Gbps/2.5GHz 16-QAM OFDM ones as well as CATV and 2.5Gbps/3.05GHz OOK ones: (a) measured at point A of Fig. 1, (b) measured at point B of Fig. 1.

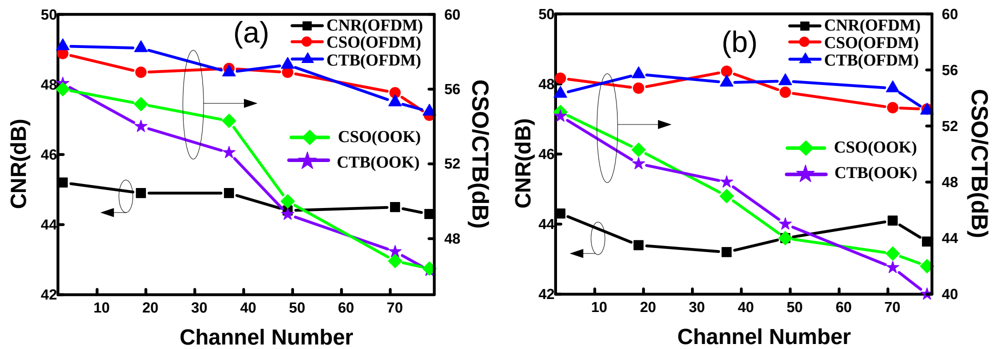

Fig. 7. The measured CNR, CSO and CTB values for transmitting signals of CATV and 5Gbps/2.5GHz 16-QAM OFDM ones as well as CATV and 5Gbps/5.55GHz OOK ones: (a) measured at point A of Fig. 1, (b) measured at point B of Fig. 1.

4. Conclusions

We have proposed and experimentally demonstrated a hybrid CATV/16-QAM OFDM in-building network over a combination of SMF and GI-POF transport. Different from current POF networks, which concentrate on short-distance POF transmission only, our novel proposed network is the first one to transmit widespread CATV and 16-QAM OFDM signals to client premises. In this system, a 1556 nm optical carrier is directly transmitted along with SMF and GI-POF. No wavelength conversion or any bridge circuit is needed between SMF access and POF connection. Generally, the GI-POF is not cheaper than twisted pair/coaxial cable and is not popular to be installed into houses now. Nevertheless, the fiber length we need to install into a house is quite short and an amateur can deploy it with minimal training and cheap tools. Instead of employing a trained person and high-precision devices to install SMF inside consumers' house, the POF with do-it-yourself characteristic will be an economic candidate for installing intra-building LAN. Furthermore, the POF cost will be reduce when it is widely accept as well. This proposed network is shown to be a prominent one to present its advancement in economy and convenience to be installed.

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