In-home networks integrating high-capacity DMT data and DVB-T over large-core GI-POF

Marta Beltrán,[1,*] Yan Shi,[2] Chigo Okonkwo,[2] Roberto Llorente,[1] Eduward Tangdiongga,[2] and Ton Koonen[2]

[1]*Valencia Nanophotonics Technology Center, Universidad Politécnica de Valencia, Camino de Vera s/n, 46022 Valencia, Spain*

[2]*COBRA Research Institute, Eindhoven University of Technology, Den Dolech 2, 5600MB Eindhoven, The Netherlands*

[*]*mbeltran@ntc.upv.es*

Abstract: The low-cost in-home distribution of full-standard digital TV jointly with high-bitrate data using 50 m long 1 mm core diameter graded-index plastic optical fiber (GI-POF) is proposed and experimentally demonstrated. Discrete multitone (DMT) modulation is demonstrated to provide an adaptive bitrate which can spectrally coexist with digital video broadcasting-terrestrial (DVB-T) signals in 470–862 MHz. A 3 Gb/s DMT signal and two DVB-T channels are generated, transmitted and received exhibiting excellent performance.

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

References and links

1. A. M. J. Koonen, H. P. A. van den Boom, E. Martinez, A. Pizzinat, P. Guignard, B. Lannoo, C. M. Okonkwo, and E. Tangdiongga, "Cost optimization of optical in-building networks," Opt. Express **19**(26), B399–B405 (2011).
2. A. Nespola, S. Straullu, P. Savio, D. Zeolla, S. Abrate, D. Cárdenas, J. Ramirez, N. Campione, and R. Gaudino, "First demonstration of real-time LED-based Gigabit Ethernet transmission on 50m of A4a.2 SI-POF with significant system margin," in *European Conference on Optical Communication* (2010), paper PD3.1.
3. H. Yang, E. Tangdiongga, S. C. J. Lee, S. Randel, H. P. A. van den Boom, and A. M. J. Koonen, "4 Gbit/s over 50-m large core diameter GI-POF using low-cost VCSEL," in *European Conference on Optical Communication* (2009), paper 3.5.1.
4. R. Kruglov, S. Loquai, C. Bunge, O. Ziemann, B. Schmauss, and J. Vinogradov, "10 Gbit/s Short-reach transmission over 35 m large-core graded-index polymer optical fiber," in *Optical Fiber Communication Conference* (2011), paper OThZ6.
5. Y. Shi, D. Visani, C. M. Okonkwo, H. P. A. van den Boom, G. Tartarini, E. Tangdiongga, and A. M. J. Koonen, "Simultaneous transmission of wired and wireless services over large core POF for in-home networks," in *European Conference on Optical Communication* (2011), paper Tu.3.C.5.
6. Y. Shi, D. Visani, C. M. Okonkwo, H. Yang, H. P. A. van den Boom, G. Tartarini, E. Tangdiongga, and A. M. J. Koonen, "First demonstration of HD video distribution over large-core POF employing UWB for in-home networks," in *Optical Fiber Communication Conference* (2011), paper OWB5.
7. ETSI EN 300 744 v1.6.1, "Digital Video Broadcasting (DVB); Framing structure, channel coding and modulation for digital terrestrial television" (2009).
8. ANSI T1.413–1998, "Network and customer installation interfaces –Asymmetric Digital Subscriber Line (ADSL) metallic interface" (1998).
9. Spain Government BOE-A-2011–5834, "Real Decreto 346/2011, de 11 de marzo, por el que se aprueba el Reglamento regulador de las infraestructuras comunes de telecomunicaciones para el acceso a los servicios de telecomunicación en el interior de las edificaciones" (2011).
10. J. Lee, R. V. Sonalkar, and J. M. Cioffi, "Multi-user discrete bit-loading for DMT-based DSL systems," in *Proceedings of IEEE Global Communications Conference* (2002), pp. 1259–1263.
11. Q. Yang, N. Kaneda, X. Liu, S. Chandrasekhar, W. Shieh, and Y. K. Chen, "Towards real-time implementation of optical OFDM transmission," in *Optical Fiber Communication Conference* (2010), paper OMS6.
12. I. Dedic, "High-speed CMOS DSP and data converters," in *Optical Fiber Communication Conference* (2011), paper OTuN1.

#176204 - $15.00 USD Received 13 Sep 2012; revised 4 Nov 2012; accepted 7 Nov 2012; published 21 Dec 2012

1. Introduction

Nowadays, optical fiber based in-home network solutions can outperform copper- and wireless- based solutions regarding performance and costs. Since the main requirements for in-home networks are low cost and ease of installation, large-core polymethyl metacrylate (PMMA)-based plastic optical fiber (POF) is a strong candidate due to its advantages of "do-it-yourself" installation [1], simple (or even no) connectorization, easy maintenance and small bending radius. The conventional standard step-index POF (SI-POF) presents a low bandwidth-distance product (< 100 MHz at 50 m) [2]. In comparison, the graded-index POF (GI-POF) with a much larger bandwidth (1.5 GHz at 50 m) is a state-of-the-art solution for high-capacity wired and wireless transmission. Until now, all studies on POF have focused on transmission of either individual baseband [3,4] and wireless services or converged services in separated frequency bands [5]. Real-time high-definition (HD) video signals have been transmitted with ultra-wideband (UWB) format over large-core GI-POF [6]. However, this approach needs electrical preprocessing before the signal being transmitted over POF. The converged wired and wireless distribution in [5] requires careful frequency planning to avoid signal interference, which is not a trivial solution for both service providers and end users.

To explore full scenario for in-home broadband application with a low-cost and adaptive solution, a converged transmission of high-capacity baseband stream employing a discrete multitone (DMT) technique and real-time full-standard digital video broadcasting-terrestrial (DVB-T) signals [7] over 50 m long 1 mm core diameter PMMA GI-POF is proposed and experimentally demonstrated. The DVB-T signal occupies the 470–862 MHz band following the regulation in Europe. We implemented a rate-adaptive DMT algorithm in which the DMT spectrum is allowed to occupy the same spectrum as for DVB-T signals. The coexistence of DMT and the DVB-T signals was achieved with a total gross bitrate of the DMT signal up to 3 Gb/s with a bit error rate (BER) below 10^{-3}, which would become a BER < 10^{-7} after reception with forward error correction (FEC) following regulation [8], and the DVB-T signal performance meets the regulated modulation error rate (MER) ≥ 23 dB as well as the carrier-to-noise ratio (CNR) ≥ 25 dB and BER < 9×10^{-5} [9]. Quality of experience (QoE) observations on the video quality showed that video images received after the POF transmission can hardly be distinguished from the source. This approach enables the effective replacement of the legacy coaxial cabling typically providing TV ports in the home.

2. In-home network scenario

The application scenario of the system is shown in Fig. 1(a). The residential gateway (RG) connects the access network to an in-home network and integrates the DVB-T signals from a master-antenna TV (MATV) in the roof. The POF provides the optical connection between the RG and each room via point-to-point links. Since GI-POF passive splitters are not currently available, a point-to-multipoint architecture may be supported by using active splitting nodes based on optoelectronic devices. We propose the baseband stream provided by the access network to be implemented with DMT modulation, which has been widely implemented in digital subscriber line (xDSL) commercial chipsets. DMT presents the unique characteristics of per subcarrier power- and bit-loading algorithm [10], which permits an excellent coexistence with the DVB-T signals, as demonstrated in the experimental work.

As shown in Fig. 1(a), both baseband DMT data connectivity and DVB-T digital TV signals can be combined at the RG and delivered over the same POF link to different terminals, such as a PC for DMT signals and a full-standard TV set for DVB-T signals. Employing the rate-adaptive DMT algorithm, the link capacity can be dynamically optimized when both a baseband service (DMT format) and multiple DVB-T channels are present using a shared wavelength approach without introducing extra optical and electrical devices.

#176204 - $15.00 USD Received 13 Sep 2012; revised 4 Nov 2012; accepted 7 Nov 2012; published 21 Dec 2012

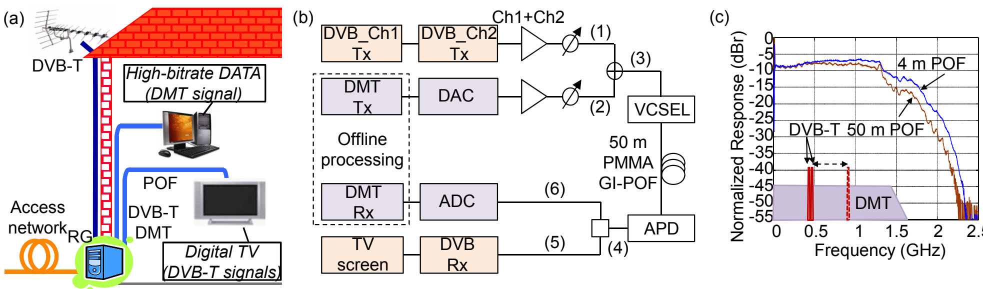

Fig. 1. (a) POF-based in-home network. (b) Experimental setup for the simultaneous transmission of DMT and two DVB-T channels over POF. (c) Frequency response of the system VCSEL-POF-APD photoreceiver.

3. Experimental setup

The experimental setup is shown in Fig. 1(b). Two DVB-T channels with the same power are generated from two commercially available transmitters (Ikusi, MAC HOME) in cascade. The transmitters can modulate analogue audio/video signals to coded orthogonal frequency division multiplexing (COFDM) digital TV signals in 470–862 MHz. The two original analogue signals are generated from a DVD player and a video camera, respectively. These signals are digitized, video coded in MPEG2 MP@ML at 10 Mb/s and audio coded in MPEG1 Layer II at 192 kb/s, and modulated in COFDM at two different RF center frequencies. Each COFDM-based DVB-T channel is configured with 6817 subcarriers (8K mode), 8 MHz bandwidth, 64-QAM modulation format, 1/32 guard interval, and 7/8 code rate, which results in the maximum useful bitrate of 31.67 Mb/s [7]. In addition, a baseband DMT-modulated data signal is generated from an arbitrary waveform generator (Tektronix AWG 7122B) with a resolution of 10 bit. Similar to DMT implementation in practical xDSL systems [8], the signal-to-noise ratio (SNR) per subcarrier is estimated at the receiver side and Chow's adaptive bit and power loading algorithm [3] is employed to maximize the bitrate.

Both the DMT and DVB-T signals in their original frequency bands are combined after amplification (19 dB and 30 dB gain, respectively) and attenuation, and directly modulate an eye-safe vertical-cavity surface-emitting laser (VCSEL) at 667 nm (Firecomms RVM665T). The VCSEL output is coupled to a 50 m PMMA GI-POF link (Optimedia OM-Giga). The signal transmitted over POF with output power of −15 dBm is detected by a Silicon avalanche photodetector (APD) (Silicon Sensor AD230-8 TO52S1) followed by a two-stage electrical amplifier with 40 dB gain. The received current is split into two paths which are connected to the DMT and DVB-T receivers separately. A digital phosphor oscilloscope (Tektronix DPO 72004) with a resolution of 8 bit is used to capture the received DMT signal for offline processing. Meanwhile, the DVB-T signals are evaluated by a digital TV analyzer (Promax, Prolink-4 Premium) and the video of a selected DVB-T channel is playing on a TV screen.

Two scenarios are considered: First, a conventional implementation of DMT combined with other services without spectral overlapping, as described in Section 4. This scenario targets to provide the "baseline" for benchmarking second scenario. In the second scenario, the optical transmission of a DMT signal overlapping with two DVB-T channels has been evaluated as a function of the channel allocation, as described in Section 5. In this scenario, the full system bandwidth is exploited to support coexisting services, as shown in Fig. 1(c).

4. Transmission performance without spectral overlapping

Two adjacent DVB-T channels centered at 474 MHz and 482 MHz are considered targeting to evaluate the lowest DMT bitrate achievable when the spectra of the DMT and DVB-T signals do not overlap. The DMT signal consists in 128 subcarriers ranging from 0 to 400 MHz. The AWG and the DPO sample at 800 MS/s and 12.5 GS/s, respectively.

#176204 - $15.00 USD Received 13 Sep 2012; revised 4 Nov 2012; accepted 7 Nov 2012; published 21 Dec 2012

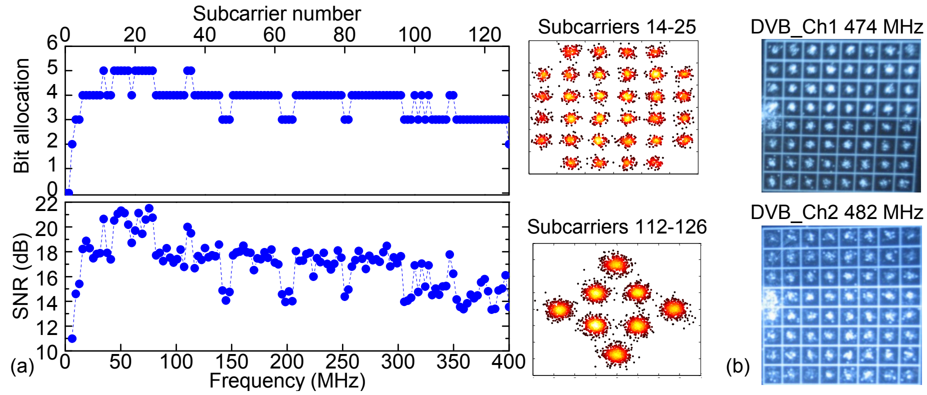

Fig. 2. Performance of the simultaneous transmission without spectral overlapping of DMT and two DVB-T channels centered at 474 MHz and 482 MHz over 50 m POF. (a) The modulation levels and the corresponding constellation diagrams and the SNR of the DMT signal. (b) Constellation diagrams of the DVB-T channels.

The DMT performance after 50 m POF is depicted in Fig. 2(a). The bit allocation ranges 2–5 bits per subcarrier dependent on the system response. For instance, 3 bits are allocated for the 112–126 subcarriers, corresponding to the 8-QAM constellation, and 5 bits for subcarriers 14–25 (32-QAM). The clear constellations indicate that the received signal quality is good after the equalization step. A bitrate of 1.5 Gb/s is achieved with a BER of 4.3×10^{-4}. The effective bitrate is 1.24 Gb/s after removing the cyclic prefix, preambles, and the 7% overhead for FEC (Reed-Solomon). The average power at point (2) in Fig. 1(b) is 0 dBm. In addition, the MER performance of the DVB-T channels after 50 m POF transmission is 26 dB and 23.4 dB, respectively. Figure 2(b) shows the corresponding 64-QAM constellation diagrams. Furthermore, the BER of the DVB-T channels is below 10^{-7} with the CNR > 25 dB. The average power at point (1) in Fig. 1(b) is −1.5 dBm.

The bitrate of the DMT signal when the two DVB-T channels are disabled is 1.85 Gb/s with a BER of 5.7×10^{-4}, corresponding to an effective bitrate of 1.5 Gb/s after FEC. The corresponding average power of the DMT signal at point (2) in Fig. 1(b) is 1.5 dBm.

5. Transmission performance with spectral overlapping

The performance of a DMT signal and two DVB-T channels has been evaluated when both signals are transmitted over POF with spectral overlapping, meanwhile maximizing the bitrate of the DMT-based data signal. The DMT signal consists of 128 subcarriers ranging from 0 to 1.5 GHz. The AWG and the DPO sample at 3 GS/s and 50 GS/s, respectively. The received signal is captured with oversampling for synchronization and quantization noise reduction. For cost-effective real implementation, digital signal processing (DSP) techniques can be alternatively employed to lower the sampling rate of the ADC and real-time processing [2,11]. Commercially available 50^{+} GS/s single-chip ADC/DAC modules can be employed [12].

The DMT performance after 50 m POF transmission in coexistence with two adjacent DVB-T channels centered at 474 MHz and 482 MHz is shown in Fig. 3(a). The DVB-T channels affect the DMT channel response, which can be noticed as a deep notch (or gap) in 440–530 MHz in the evaluated bit and power allocations and SNR. Nevertheless, DMT with bit-loading adapts well to the high level of interference from DVB-T. No bits are allocated for subcarriers 38–43, which results in a low SNR (< 6 dB) of these subcarriers. In other words, the low SNR of the DMT signals at these frequencies introduce less noise to the DVB-T signal. Apart from this notch, the maximum bit allocation value is 3 bits per subcarrier and the bit allocation decreases to 0 or 1 for the higher frequency region (>1.3 GHz) dependent on the system response. As shown in Fig. 3(a), 3 bits (8-QAM constellation) are allocated for the

#176204 - $15.00 USD Received 13 Sep 2012; revised 4 Nov 2012; accepted 7 Nov 2012; published 21 Dec 2012

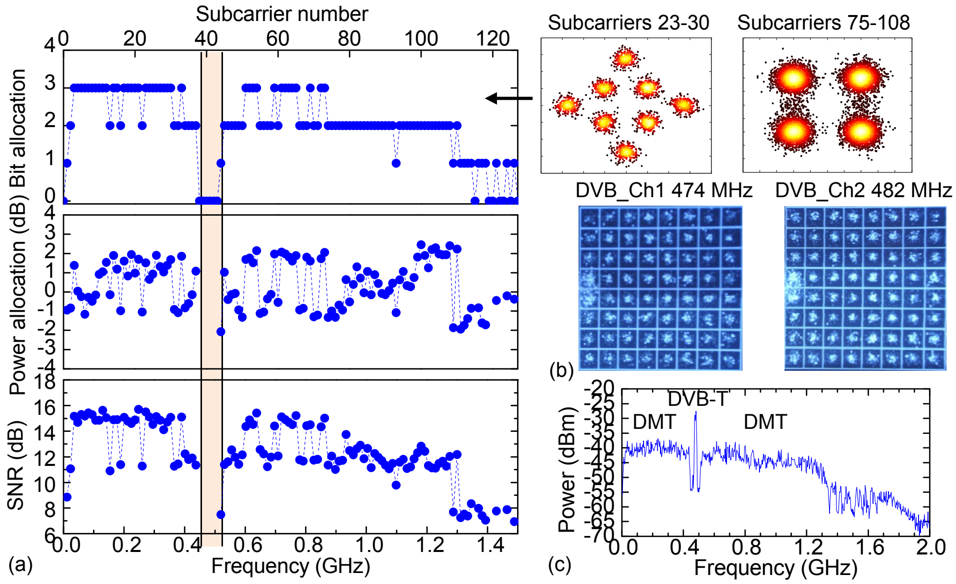

Fig. 3. Performance of the simultaneous transmission with spectral overlapping of DMT and two DVB-T channels centered at 474 MHz and 482 MHz over 50 m POF. (a) The modulation levels and the corresponding constellation diagrams, the relative power levels, and the SNR of the DMT signal. (b) DVB-T constellation diagrams. (c) Spectrum at point (4) in Fig. 1(b).

23−30 subcarriers, while 2 bits (QPSK constellation) are allocated for subcarriers 75−108. The discrete SNR after bit-loading is due to the non-uniform power allocation to each subcarrier. A DMT bitrate of 2.96 Gb/s is achieved with a BER of 5.3×10^{-4}. The effective bitrate is 2.4 Gb/s after removing the cyclic prefix, preambles, and the 7% overhead for FEC. The average power at point (2) in Fig. 1(b) is 6.6 dBm. In addition, the MER performance of the DVB-T channels after 50 m POF transmission is 23.7 dB and 25.3 dB, respectively. Figure 3(b) shows the corresponding 64-QAM constellation diagrams. Furthermore, the BER of the DVB-T channels is below 10^{-7} with a CNR of 25.3 dB and 26.7 dB, respectively, as shown in Fig. 3(c). The average power at point (1) in Fig. 1(b) is −2 dBm.

Additionally, the DVB-T channels exhibit a MER of 26.5 dB and 28.1 dB, respectively, at point (3) in Fig. 1(b). Hence, the POF system induces a MER degradation of 2.8 dB.

The DMT bitrate when the two DVB-T channels are disabled is 4 Gb/s with a BER of 4.8×10^{-4}, corresponding to an effective bitrate of 3.3 Gb/s after FEC. The average power of the DMT signal at point (3) in Fig. 1(b) is −2.5 dBm. A MER of 31 dB and 32 dB is achieved for the DVB-T channels, respectively, when the DMT signal is disabled. The average power at point (3) in Fig. 1(b) is −7 dBm. In addition, the two DVB-T channels exhibit a MER of 34 dB at point (3) in Fig. 1(b) when the DMT signal is disabled. Hence, the POF system induces a degradation of 3 dB and 2 dB in the MER of the DVB-T channels, respectively.

The DMT signal is capable of supporting the broadcasting of the coexistent DVB-T channels when the channels are not adjacent as well. The DMT performance after 50 m POF transmission in coexistence with two DVB-T channels centered at 474 MHz and 586 MHz is depicted in Fig. 4(a). The DVB-T channels affect the DMT channel response, which can be noticed as two deep gaps in 449−508 MHz and 567−615 MHz in the bit and power allocations and SNR. Nevertheless, DMT with bit-loading adapts well to the high level of interference from DVB-T when the two DVB-T channels are non-adjacent. No bits are allocated for subcarriers 39−42 and 49−51, which results in the SNR < 6 dB of these subcarriers. A DMT bitrate of 2.94 Gb/s is achieved with a BER of 2.1×10^{-4}, corresponding to an effective bitrate of 2.4 Gb/s after FEC. The average power at point (2) in Fig. 1(b) is 6.8

#176204 - $15.00 USD Received 13 Sep 2012; revised 4 Nov 2012; accepted 7 Nov 2012; published 21 Dec 2012

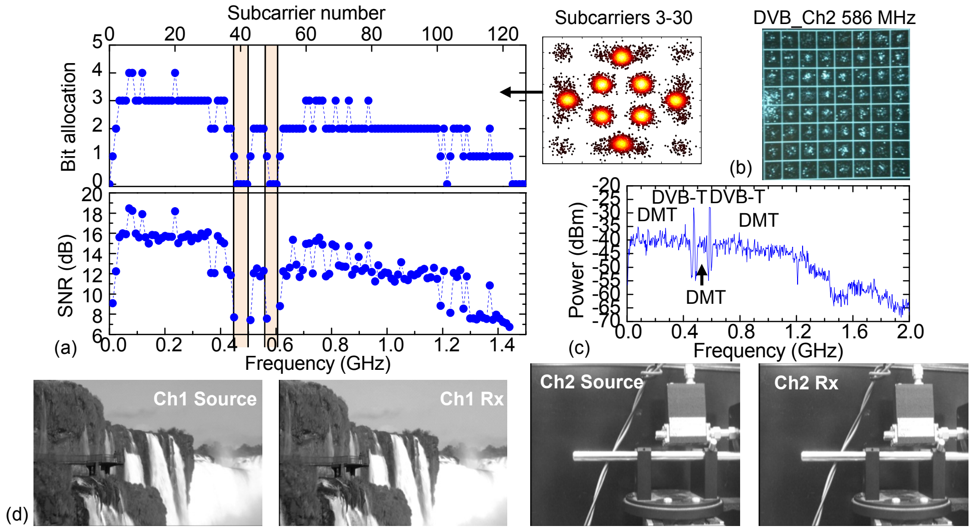

Fig. 4. Performance of the simultaneous transmission with spectral overlapping of DMT and two DVB-T channels centered at 474 MHz and 586 MHz over 50 m POF. (a) The modulation levels and the corresponding constellation diagram and the SNR of the DMT signal. (b) Constellation diagram of the DVB-T channels. (c) Received spectrum at point (4) in Fig. 1(b). (d) Snapshot of DVB-T video stream: video source output and received video.

Table 1. 50 m POF Transmission Performance of DMT in Coexistence with Two DVB-T Channels

DVB_Ch1	DVB_Ch2	DMT Bitrate	DMT BER	DVB_Ch1 MER	DVB_Ch2 MER
578 MHz	586 MHz	3.19 Gb/s	1.2×10^{-4}	23.7 dB	24.6 dB
682 MHz	690 MHz	3.01 Gb/s	3.5×10^{-4}	23.5 dB	24.8 dB
474 MHz	506 MHz	3.14 Gb/s	2.5×10^{-4}	24.6 dB	24.4 dB
474 MHz	682 MHz	2.84 Gb/s	1.8×10^{-4}	23.6 dB	23.7 dB
474 MHz	858 MHz	2.80 Gb/s	4.7×10^{-4}	23.4 dB	24.5 dB

dBm. In addition, the MER performance of the DVB-T channels after 50 m POF transmission is 23.5 dB for the two channels. Figure 4(b) shows the corresponding 64-QAM constellation diagram. Furthermore, the BER of the DVB-T channels is below 10^{-7} with a CNR of 26.6 dB for the two channels, as shown in Fig. 4(c). The average power at point (1) in Fig. 1(b) is −1 dBm. We took the snapshots of the original video sources and the received video after the optical transmission. From the comparison shown in Fig. 4(d) we can clearly observe that the transmitted video signal over 50 m POF maintains performance without visible degradation.

Table 1 summarizes 50 m POF transmission performance of the DMT signal in coexistence with two DVB-T channels as a function of the channel allocation. Performance can be approximately maintained independent on the DVB-T frequencies provided that the level of the DVB-T channels at point (3) in Fig. 1(b) is set to compensate for the frequency response of the system. This is verified by employing a low-pass filter (600 MHz) at point (1) in Fig. 1(b). Performance is maintained when two adjacent DVB-T channels centered at 682 MHz and 690 MHz are considered by compensating the 9 dB attenuation induced by the filter in both channels. The average power at point (1) in Fig. 1(b) is 0.5 dBm. This also for non-adjacent DVB-T channels centered at 474 MHz and 682 MHz by compensating the 9 dB attenuation in the channel at 682 MHz, resulting in 0 dBm at point (1) in Fig. 1(b).

6. Conclusion

We have proposed and experimentally demonstrated the simultaneous transmission of DMT-based data and real-time DVB-T video signals over 50 m PMMA GI-POF. The system takes advantage of the bit and power loading algorithm to realize an adaptive bitrate for the DMT

#176204 - $15.00 USD Received 13 Sep 2012; revised 4 Nov 2012; accepted 7 Nov 2012; published 21 Dec 2012

signal when an overlapping frequency band is introduced. 3 Gb/s DMT transmission is demonstrated with BER < 10^{-3} suitable for reception with FEC following ANSI T1.413 regulation, in coexistence with two DVB-T channels exhibiting a MER higher than 23 dB regulated limit. The performance maintains within the 470−862 MHz digital TV band in Europe independently on the spectral allocation of the DVB-T channels. This work validates the idea of using 1 mm diameter POF link as a low-cost common infrastructure for in-home networks capable of transmitting multiple services with self-adaption coexistence mechanism.

Acknowledgments

This work has been supported in part by the European Commission through the FP7 ICT-4-249142 FIVER project, and by the Spain project IPT-430000-2010-072 IT-HOGAR.

#176204 - $15.00 USD Received 13 Sep 2012; revised 4 Nov 2012; accepted 7 Nov 2012; published 21 Dec 2012