OFDM-WDM LR-PON with ultra-bendable fiber for last-mile distribution of quintuple-play service

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The provision of quintuple-play services along wavelength division multiplexed (WDM) long-reach passive optical networks (LR-PONs) employing an ultra-bendable fiber in last-mile distribution is demonstrated experimentally. Particularly, the simultaneous transmission of three 100-GHz-spaced optical channels for the provision of double sideband orthogonal frequency-division multiplexing (OFDM) wireless and wired quintuple-play services to the premises of users located at 75, 85, and 100 km away from the central office is demonstrated. The OFDM-WDM LR-PON is tested considering the last-mile fiber distribution suffering from severe bending conditions without optical dispersion compensation. The experiments are performed for a worst last-mile fiber bending case emulated by considering a Corning® ClearCurve® fiber experiencing 20 bends and a bend radius of 7.5 mm. All the OFDM signals received at the premises of users present error vector magnitude (EVM) levels compliant with the EVM thresholds of the corresponding standards. An EVM degradation in the OFDM signals received by each user not exceeding 0.8 dB due to the last-mile distribution fiber is achieved.

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The integration of wireless and wired services in a single hybrid access network is a promising solution to provide end users with high data-rate wireless and wired connectivity and to allow network operators to have cost savings[1−4]. Recently, a long-reach passive optical network (LR-PON) that supports wired and wireless orthogonal frequency-division multiplexing (OFDM) signals and uses wavelength division multiplexing (WDM) has been proposed to provide high data-rate wireless/wired multi-user access[5]. An illustrative scheme of the proposed WDM LR-PON is depicted in Fig. 1. The optical line termination (OLT) is connected to the remote node (RN) via the feeder fiber, whose length is usually around 80 km. Moreover, the distribution fiber is used to connect the RN to the optical network unit (ONU) installed at the premise of users. The distribution part of the network is divided in two links. One is the RN-adapter link representing most of the distribution part of the network. This link may reach 30 or 40 km. The other is the last-mile distribution link representing the last part of the network. This link is used to provide end users with services. The adapter shown in Fig. 1 represents the interface between these two distribution links. This fully integrated network is capable of delivering quintuple-play OFDM services, such as wired broadband Internet and voice/phone data, using a custom OFDM signal providing features similar to standard Gigabit Ethernet (GbE), mobile voice/phone using worldwide interoperability for microwave access (WiMAX) and long-term evolution (LTE), wireless Internet, using WiMAX and LTE, home security/control service, using LTE, and high definition audio and video contents, using ultra wideband (UWB) technology. The quality of these quintiple-play services offered to end users and the inclusion of other OFDM services in the proposed network benefit from the centralized impairment compensation realized at the OLT[6]. This centralized compensation approach is enabled by the OFDM nature of the different signals used to provide quintuple-play services, allowing reduced deployment costs and, in turn, operational and management network savings.

The provision of quintuple-play services to end users using the OFDM WDM LR-PON was demonstrated experimentally[7]. In that proof-of-concept, the provision of quintuple-play services to ONUs installed 100 km away from the OLT with error vector magnitude (EVM) compliant levels in all the services was achieved. A 100-km-long OLT-ONU distance was reached using a feeder fiber connecting the OLT to the RN and a distribution fiber connecting the RN to each ONU. The

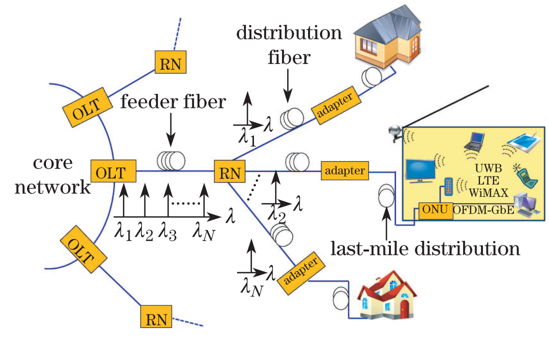

Fig. 1. Illustrative scheme of the WDM LR-PON used for provisions of quintuple-play services to end users with last-mile distribution using ultra-bendable fiber.

feeder fiber has a maximum length of 75 km, whereas the dstibution fiber has a maximum length of 25 km. However, in these experiments, the deployment constraints of the last-mile distribution were not considered. These constraints are commonly associated with unavoidable fiber bends realized to install the fibers up to the premises of users.

In the past, several solutions have been proposed to provide in-building fiber distribution: multi-mode fiber (MMF)[8,9], single-mode plastic optical fiber (POF)[10], multi-mode POF[10], and bend insensitive fiber[9,10]. The simultaneous distribution of UWB, Wi-Fi 802.11 g, and cable TV along 600 m of MMF was demonstrated in Ref. [8], whereas unlicensed Wi-Fi was transmitted alone along 100 m of MMF in Ref. [9]. In both cases, the signals received from the access network are photodetected, and the use of vertical cavity surface emitting lasers for the modulation and transmission of signals along the in-building infrastructure is considered. By contrast, the work reported in Ref. [10] employs an optical adapter between the access and in-building networks, thereby enabling a streamlined integrated architecture. Accordingly, the transmission of a triple-play OFDM bundle comprising LTE, WiMAX, and UWB signals was demonstrated along a 20-km-long single-mode fiber (SMF) PON, considering a maximum in-building fiber distance of 200 m.

In this letter, the provision of quintuple-play services to the premises of users along an all optical streamlined OFDM-WDM LR-PON reaching 100 km and employing an ultra-bendable fiber for last-mile distribution is demonstrated experimentally under extremely severe bending conditions. Particularly, the simultaneous transmission of three optical channels along LR-PONs distances indicated for the integration of metro and acess networks in a single hybrid wireless-wired optical network with a last-mile distribution fiber comprising 20 bends (bend radius of 7.5 mm) is demonstrated.

The OFDM-WDM employing ultra-bendable optical fiber for last-mile distribution is introduced and the different network elements are described. Figure 2(a) depicts the downstream path of the OFDM-WDM LR-PON employing an ultra-bendable optical fiber for last-mile distribution. This network infrastructure represents an extension of the WDM LR-PON reported in Ref. [7] by introducing an ultra-bendable optical fiber in the last-mile of the network. The WDM LR-PON employing an ultra-bendable fiber for last-mile distribution is composed of the following: (i) an OLT installed at the central office, where the different multi-format OFDM signals used to provide the quintuple-play service are combined and the centralized impairment compensation is realized, (ii) a feeder fiber used to connect the OLT to the RN, (iii) a RN, where optical amplification is accomplished to compensate for the fiber losses[11], (iv) a distribution fiber used to connect the RN to the adapter, (v) a last-mile distribution fiber used to deliver the services to the premise of users, and (vi) an ONU installed at the premise of users, where the multi-format OFDM signals are photodetected and filtered. Without any type of transmodulation or up/down conversion, the ONU is also where the quintuple play services are offered to end users. The adapter represents the interface between the distribution and the last-mile ultra bendable SMFs. This interface is implemented using a conventional fiber connector that enables the integration of metro/access/in-building networks in a single all-optical network with wired-wireless convergence and no need for optic-electric-optic conversion or special fiber adapters.

The OFDM-GbE, LTE, WiMAX, and UWB signals are combined and multiplexed using offline digital signal processing (DSP). Figure 2(b) shows a schematic of the conventional OFDM transmitter used to generate each OFDM signal. The parameters of the multi-format OFDM signals are presented in Table 1. The spectrum of the OFDM signal bundle occupies the frequency range between 1 and 4.8 GHz. UWB band #1 is not transmitted to avoid interference with WiMAX signal according to current detect and avoid (DAA) regulation. Additionally, UWB bands with central frequencies higher than UWB band #3 are also not considered because commercial devices available nowadays operate only in the first three UWB bands. After generation of the OFDM signals bundle, nine radio-frequency (RF) pilots are inserted in the free spectrum close to the edges of the different OFDM signals[6]. These RF-pilots used for channel sounding enable the estimation of the predistortion characteristic used by the centralized compensation block to reduce the channel-induced impairments. Further information regarding the centralized compensation approach and the frequencies of the RF-pilots can be found in Refs. [6,7]. The electrical multi-format signals are generated using an arbitrary waveform generator (AWG) operating in the continuous mode at 20 Gs/s. The power of the multi-format OFDM signals is adjusted to achieve a modulation index of 9%[6]. The modulation index is defined as $m = V_{\mathrm{RMS}}/V_x$, where V_{RMS} is the root-mean-square (RMS) voltage of the multiplexed signal applied to the Mach-Zehnder modulator (MZM) arm and V_x is the switching voltage of the MZM. The desired

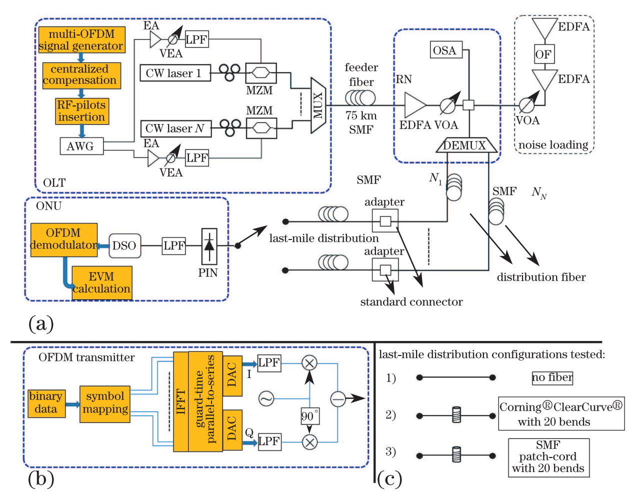

Fig. 2. (a) Schematic diagram of the downstream path of the OFDM-WDM LR-PON employing ultra-bendable optical fiber for last-mile distribution; (b) scheme of the OFDM transmitter used to generate the multi-format OFDM signals; (c) configurations under analysis for the last-mile distribution of the quintuple-play services to end users. DEMUX: demultiplexer; MUX: multiplexer; DSO: digital storage oscilloscope; VOA: variable optical attenuator.

Table 1. Parameters of the OFDM-GbE, LTE, WiMAX, and UWB Signals

Parameters	OFDM-GbE	LTE	WiMAX	UWB 2	UWB 3
Central Frequency (GHz)	1.5	2.6	3.5	3.96	4.49
Nominal Bandwidth (MHz)	1 000	31	23	528	528
Symbol Duration (ns)	132	71.4×10^3	12.6×10^3	312.5	312.5
Guard Time (ns)	4	4.7×10^3	1.4×10^3	70.1	70.1
Maximum Bit-rate (Mb/s)	1.2×10^3	33.3	30.4	640	640
Number of Subcarriers (FFT Size)	128	2 048	256	128	128
Number of Data Subcarriers	81	1 190	192	100	100
Number of Pilot Subcarriers	8	12	8	12	12
Number of Guard Subcarriers	39	846	56	16	16
Symbol Mapping	QPSK	QPSK	QPSK	QPSK	QPSK
EVM Limits (dB)	–11	–15.1	–20	–14.5	–14.5

voltage level is achieved by adequately controlling the attenuation introduced by variable electrical attenuators (VEAs, 18 GHz bandwidth) and electrical amplifiers (EAs, gain of 26 dB, –3-dB bandwidth between 0.7 and 18 GHz). The power of the multiplexed signal prior predistortion is equally shared by the OFDM-GbE, LTE, WiMAX, and UWB signals. Prior to be converted to the optical domain, the multiplexed signal is filtered by a low-pass filter (LPF) with a –3-dB bandwidth of 8.15 GHz to reduce the electrical noise power reaching the modulator. The electro-optic conversion is ensured by continuous wave (CW) lasers (linewidth lower than 10 MHz) and 10-Gb/s modulators biased at the quadrature point and with zero chirp. Before being launched into the feeder fiber, the optical channels to be delivered to each ONU are multiplexed using an arrayed waveguide grating with 100 GHz of channel spacing.

The feeder fiber consists a 75-km-long SMF (dispersion parameter of 17 ps/(nm·km)). At the RN, the fiber losses are compensated using an erbium-doped fiber amplifier (EDFA). Additionally, a noise loading circuit is used to adjust the optical signal-to-noise ratio (OSNR), defined in a reference bandwidth of 0.1 nm, of each optical channel. An optical spectrum analyzer (OSA) with a resolution bandwidth of 0.16 pm is used to monitor the spectrum of the multi-format OFDM signals at the RN. Each wavelength of the WDM signal is demultiplexed using an arrayed waveguide grating with features identical to the one used at the OLT side and then launched to the corresponding distribution fiber (dispersion parameter of 17 ps/(nm·km)). Different distribution fiber lengths are analyzed. Particularly, distribution fiber lengths ranging between 0 km (adapter installed at the RN) and 50 km (adapter 50 km far away from the RN) are assessed. The average optical power of the signal launched into the feeder and distribution fibers is kept below 1 dBm to avoid degradation because of nonlinear fiber effects.

Three last-mile fiber configurations are analyzed in this letter (Fig. 2(c)): (i) no last-mile fiber distribution is employed (reference case), (ii) 1 km of a ClearCurve® ZBL SMF, and (iii) a conventional SMF patch cord with a length of 2 m. The last-mile distribution fiber shown in Fig. 2 is rolled around a board marker with 20 bends and a bend radius of 7.5 mm to emulate a worst case scenario representing the last-mile fiber deployment stage where severe fiber bends may occur.

At the ONU, the signals are photodetected by a 9-GHz PIN photodiode with a responsivity of 0.75 A/W, filtered by a LPF with a –3-dB bandwidth of 4.85 GHz to reduce the noise power and the out-of-band distortion components, and digitized by a real-time oscilloscope operating at 10 Gs/s. DSP algorithms are then applied to the digitized signal waveform to demodulate the multi-format OFDM signals. These algorithms comprise RF carrier recovery, time synchronization, down-conversion, FFT window synchronization, common phase error compensation, and equalization. In addition, the EVM of each received OFDM signal is also evaluated and compared with the EVM limits stated in each standard. The EVM limits of the multi-format OFDM signals are presented in Table 1. The EVM limit of the OFDM-GbE signal corresponds to a bit error ratio (BER) of 10^{-4} in a noise-impaired quadrature phase-shift keying (QPSK) system.

Figure 3 shows the power spectral density (PSD) of the multi-format OFDM signal measured at different points of the experimental setup. The OSNR is set to 30 dB. Figure 3(a) shows the PSD of the pre-distorted signals after insertion of the RF-pilots used for channel sounding. It shows that the PSD of the signals with high central frequencies (UWB signals) increases with

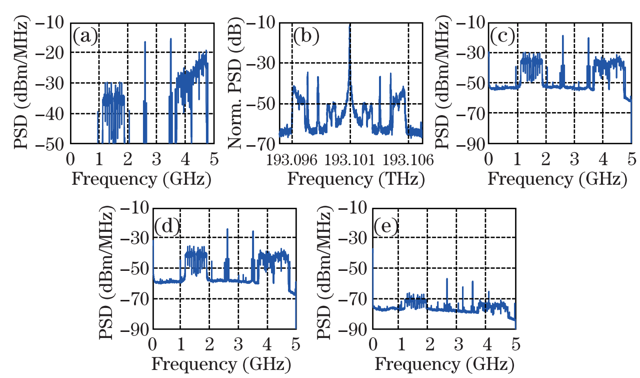

Fig. 3. Measured PSD of the signals at different points of the system setup. (a) After insertion of the RF-pilots used for channel sounding; (b) at the input of the demultiplexer installed at the RN; (c) at the output of the LPF at the ONU, considering the ONU directly connected to the RN (reference); (d) at the output of the LPF at the ONU, considering a LR-PON employing the lat-mile ClearCurve® ZBL fiber; (e) at the output of the LPF at the ONU, considering a LR-PON with a 2-m SMF patch cord.

increasing frequency. The increase in PSD is implemented at the centralized compensation block using the information provided by the RF-pilots used for channel estimation[6], and it is needed to overcome the amplitude reduction caused by the limited frequency response of the system devices and the fiber dispersion-induced power fading[12]. Figure 3(b) shows the PSD of the optical signal at the input of the demultiplexer installed at the RN. Two main aspects should be retained from the inspection of Fig. 3(b). First, the PSD of the optical signal consists in the double sideband version of the multi-format OFDM signals and in the high-power optical carrier. The transmission of the wireless and wired quintuple-play services along the proposed LR-PON is realized without using single sideband modulation or any type of optical dispersion compensation. The high power level of the optical carrier due to the quadrature bias point of the modulator leads to a high carrier-to-signal power ratio and can be further improved by moving the modulator bias point closer to the minimum of the power transmission characteristic[13]. The second aspect is related to the high amplitude levels still noted in the OFDM signals with higher central frequencies. They are needed to compensate the power fading induced by dispersion, which affects the signal amplitude only after the photodetection process, and the PIN and receiver LPF bandwidth limitations. Figures 3(c)–(e) show the PSD of the photodetected current at the output of the LPF considering that the ONU is directly connected to the RN, the last-mile ClearCurve® ZBL fiber, and the 2-m SMF, respectively. A comparison between Figs. 3(c) and (d) shows that the attenuation introduced by the 1-km-long ClearCurve® ZBL fiber comprising 20 bends is quite reduced. By contrast, Fig. 3(e) shows that the maximum PSD of the received multi-format OFDM signals drops almost down to the noise floor when the 2-m SMF with 20 bends is employed. Further investigation shows that the peak PSDs of the different OFDM signals are 5 and 35 dB below the reference case for the ClearCurve® ZBL fiber configuration and the SMF, respectively. These attenuation levels of the PSD of the photodetected signals are in accordance with the optical power attenuations measured: around 2 dB for the ClearCurve® ZBL fiber and around 18 dB for the SMF.

Figure 4 depicts the EVM of the OFDM-GbE, LTE, WiMAX, and UWB bands as a function of the OSNR. These results are obtained considering the adapter installed at the RN. Additionally, the EVM results for the three last-mile distribution fiber configurations introduced before, as well as the EVM limit of each OFDM signal (as reference), are presented. A detailed analysis of Fig. 4 shows that an additional EVM degradation induced by the 1-km-long ClearCurve® ZBL fiber comprising 20 bends not exceeding 0.4 dB is achieved when compared with the reference situation (without last-mile fiber distribution). By contrast, the 2-m SMF with 20 bends leads to an EVM degradation in the different OFDM signals higher than 7 dB.

Compared with the SMF situation, EVM-compliant levels in all the five OFDM signals can still be achieved in a 75-km-long LR-PON employing the 1-km-long ClearCurve® ZBL fiber under severe bending conditions (Fig. 4). Thus, the following study is focused in the evaluation of the EVM of the multi-format OFDM signals when the ONU is farther away from the RN, i.e., when the length of the distribution fiber represented in Fig. 2 increases. This study is realized considering that the adapter is still connected to the ONU installed at the user premises via the 1-km-long ClearCurve® ZBL fiber comprising 20 bends.

Figure 5 shows the EVM of the multi-format OFDM signals as a function of the OLT-adapter distance for an OSNR of 30 dB. The OLT-adapter distances represented in Fig. 5 correspond to RN-adapter distances of 0, 10, 25, 35, and 50 km. Negligible EVM degradation (lower than 0.5 dB) due to signal transmission along the 1-km-long ClearCurve® ZBL fiber comprising 20 bends is observed for OLT-adapter distances up to 125 km. This conclusion remains valid regardless the signal of the OFDM bundle considered. The EVM degradation observed in Fig. 5 when the OLT-adapter distance increases can be attributed to the dispersion-induced power fading[6,7]. For an OLT-adapter distance of 125 km, an EVM penalty of 0.3 dB is obtained in UWB band #2 when compared with the EVM limit of the UWB standard (−14.5 dB, Fig. 5). Although this EVM penalty indicates that the transmission of the multi-format OFDM signals along 125-km-long LR-PONs cannot be

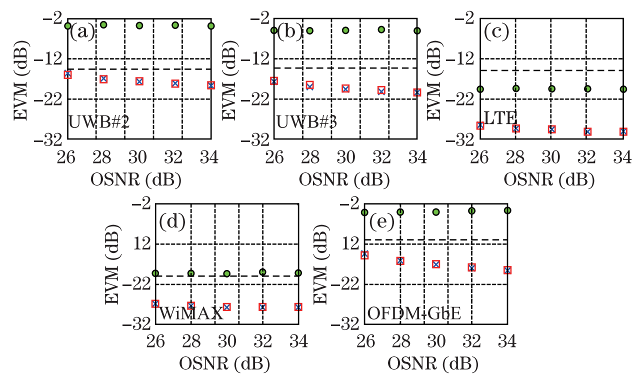

Fig. 4. EVM of the multi-format OFDM signals as a function of the OSNR considering the adapter installed at the RN. Results obtained without last-mile distribution fiber (squares), 1-km ClearCurve® ZBL fiber (crosses), and 2-m SMF (circles). EVM limit of each OFDM signal (dashed lines).

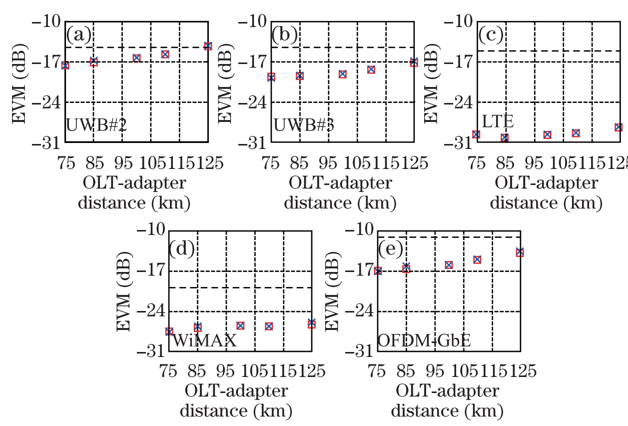

Fig. 5. EVM of the multi-format OFDM signals as a function of the OLT-adapter distance. Results obtained without last-mile distribution fiber (squares) and 1-km ClearCurve® ZBL fiber (crosses). EVM limit of each OFDM signal (dashed lines).

accomplished with EVM-compliant levels, the system can be further improved through adequate optimization of the power sharing between the different OFDM signals. For instance, the results shown in Fig. 5 suggest that a fraction of the power attributed to LTE and WiMAX signals can be transferred to UWB signals because the EVMs of LTE and WiMAX after the 125-km-long LR-PON still present a comfortable margin to the corresponding EVM limits. Figure 5 shows also that the EVM of UWB band #2 is worse than the EVM of UWB band #3. This finding is due to the coarse tuning of the amplitude level realized by the centralized impairment compensation approach[6,7].

The transmission of the multi-format OFDM-based signals along a WDM LR-PON employing the 1-km-long ClearCurve® ZBL fiber with 20 bends for last-mile provision of quintuple-play service to end users is demonstrated experimentally. Particularly, the EVM of the OFDM-GbE, LTE, WiMAX, and UWB signals carried in three optical channels with 100 GHz of channel specing is evaluated. Each one of the three optical channels is used to diliver the OFDM-based signals to three ONUs: ONU 1, ONU 2, and ONU 3 are served by the channels located at 193.0, 193.1, and 193.2 THz, respectively. Additionally, the adapters serving ONU 1, ONU2, and ONU 3 are installed at 75, 100, and 85 km far away from the OLT, respectively. The OSNR of each optical channel is 30 dB. A detailed discussion concerning the implementation of the WDM LR-PON experimental setup is presented in Ref. [7].

This study is focused only in the physical impairments of the downstream path of the access network shown in Fig. 1. In addition, only three wavelengths and a 100-GHz channel spacing are employed because of the limitations of the equipment available in our laboratory. However, when deployed, the access network must enable bi-directional connectivity. In Ref. [5], this bi-directional connectivity is ensured using different wavelengths for both transmission directions. Considering that the bandwidth available for WDM transmission is about 30 nm (bandwidth of EDFAs operating in C-band) and assuming that a guard-band exists between the wavelengths used for the downsteam and upstream paths of 4 nm, the 100-GHz spaced WDM LR-PON is capable of supporting 16 subscribers per fiber. The channel spacing may be further reduced to 25 GHz or even 12.5 GHz (the maximum frequency of the OFDM signals bundle is 4.8 GHz). In these cases, the maximum number of subscribers covered by each fiber are 65 and 130 for 25 and 12.5 GHz, respectively. For these tighter spacings, a detailed analysis on the impact of the inter-channel crosstalk on the performance degradation of the multi-format OFDM signals is still required.

Our main interest is the assessment of delivering quintuple-play services to end users using last-mile fiber distribution under severe bending conditions. The EVMs of the multi-format OFDM signals achieved in the three last-mile fiber distribution configurations shown in Fig. 2(c) are compared. The WDM LR-PON supporting the transmission of the multi-format OFDM signals in the absence of last-mile fiber distribution was studied in Ref. [7]. The corresponding EVM levels are shown in this work only as reference.

Figure 6 depicts the PSD of the OFDM signals received by ONU 1, ONU 2, and ONU 3. The received spectra when the last-mile distribution is performed using the 1-km-long ClearCurve® ZBL fiber and the 2-m SMF patch cord comprising 20 bends are shown. Figure 6 shows that the multi-format OFDM signals are adequately received by the three ONUs when the ClearCurve® ZBL fiber is employed. By contrast, the signals received by the ONUs when the SMF is used suffer from a significant power attenuation because of the 20 bends employed. This power attenuation is more critical in ONU 2 (the OLT-adapter distance is 100 km) because the peak PSD of OFDM-GbE and UWB signals is almost at the level of the noise PSD. Compared with the peak PSD of the signals received when the ClearCurve® ZBL fiber is employed, the peak PSD attenuation suffered by the OFDM signals transmitted along the SMF patch cord is around 31 dB (Fig. 6). This attenuation turns out in an optical power attenuation difference (between the ClearCurve® ZBL fiber and SMF patch cord cases) of about 15.5 dB. Considering that the optical power attenuation introduced by the ClearCurve® ZBL fiber is around 2 dB, the SMF patch cord introduces an optical power attenuation of 17.5 dB. This result is in agreement with the SMF attenuation identified before. When the ClearCurve® ZBL fiber is used for last-mile distribution, the PSD of the signal and noise are both attenuated when the distance between the adapter and the RN increases (Fig. 6). This finding is ascribed to the additional loss introduced by the distribution fiber connecting the RN to the adapter. However, in the case of the SMF, only the signal PSD is attenuated when the distance between the adapter and the RN increases, whereas the noise PSD remains unchanged. This result is due to the level of the average optical power at the PIN input when the SMF patch cord is used is quite low. In this situation, the dominant noise source is the electrical noise introduced by the receiver front-end. By contrast, in the ClearCurve® ZBL fiber situation, the dominant noise source is the amplified spontaneous emission noise introduced by the optical amplifiers.

Tables 2–4 show the EVM of the multi-format OFDM signals received by each ONU of the WDM LR-PON in the absence of last-mile fiber distribution (reference case), employing the 1-km-long ClearCurve® ZBL fiber comprising 20 bends and the 2-m-long SMF patch cord comprising 20 bends, respectively. A comparison between the results of Tables 2 and 3 shows that the transmission of the OFDM signals along the ClearCurve® ZBL fiber comprising 20 bends leads to an EVM degradation not exceeding 0.8 dB. Table 3 shows also that EVM-compliant levels in all the OFDM signals are achieved in the three ONUs even under the severe ClearCurve® bending conditions. By contrast, when the multi-format OFDM signals are transmitted along the SMF suffering similar bending conditions, an EVM degradation, that may exceed 15 dB is observed. The non-available (NA) EVM levels in Table 4 for some OFDM signals is attributed to the fact that the signals were not demodulated because of the very poor SNR of the received signal, as predicted by the spectra presented in Fig. 6.

In conclusion, the provision of wired and wireless quintuple-play service along a multi-format OFDM

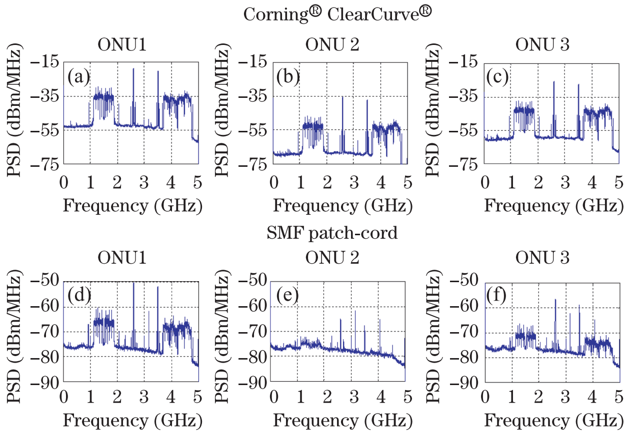

Fig. 6. Measured PSD of the signals received by the ONU 1, ONU 2, and ONU 3 when the ClearCurve® ZBL fiber and the SMF are used as physical support for the last-mile distribution.

Table 2. EVM of Different OFDM Signals Transmitted in the WDM LR-PON without Last-mile Fiber Distribution (Unit: dB)

	ONU 1	ONU 2	ONU 3
OFDM-GbE	–16.8	–16.7	–16.6
LTE	–30.0	–29.8	–29.5
WiMAX	–27.7	–27.2	27.2
UWB 2	–17.4	–16.6	–16.6
UWB 3	–19.2	–18.5	–18.8

Table 3. EVM of Different OFDM Signals Transmitted in the WDM LR-PON Employing the ClearCurve® ZBL Fiber Comprising 20 Bends (Unit: dB)

	ONU 1	ONU 2	ONU 3
OFDM-GbE	–16.7	–16.5	–15.8
LTE	–30.1	–29.7	–29.3
WiMAX	–27.7	–27.4	–27.1
UWB 2	–17.4	–16.4	–16.0
UWB 3	–19.2	–18.4	–18.4

Table 4. EVM of Different OFDM Signals Transmitted in the WDM LR-PON Employing the SMF Comprising 20 Bends (Unit: dB)

	ONU 1	ONU 2	ONU 3
OFDM-GbE	–9.4	NA	–3.5
LTE	–24.6	–11.4	–19.8
WiMAX	–24.3	–10.2	–19.0
UWB 2	–9.6	NA	–3.7
UWB 3	–11.4	NA	–4.5

WDM LR-PON employing a ClearCurve® ZBL fiber in the last-mile distribution is demonstrated experimentally under severe bending conditions. An EVM degradation not exceeding 0.8 dB in each signal of the OFDM bundle due to the ultra-bendable Corning® ClearCurve® fiber is demonstrated. This negligible EVM degradation is obtained for the simultaneous provision of quintuple-play services along 100-GHz-spaced WDM LR-PONs serving three ONUs located at 75, 85, and 100 km away from the central office and considering the last-mile fiber rolled around a board marker with 20 bends and a bend radius of 7.5 mm. The experimental results show that the ClearCurve® ZBL fiber is quite robust to tight fiber bends, making it a powerful solution for the provision of quintuple-play services in the last-mile part of the proposed OFDM-WDM LR-PON. This network benefits from the convergence of wired and wireless services in a single all-optical and fully integrated infrastructure to connect the central office with the premise of users. Given that the ultra-bendable fiber is also commonly employed in the in-building network, its deployment for the last-mile distribution avoids the need for expensive interfaces that may be required to connect the distribution fibers of the access network to the in-building network.

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