Transmission of OFDM wired-wireless quintuple-play services along WDM LR-PONs using centralized broadband impairment compensation

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Abstract: The simultaneous transmission of four orthogonal frequency-division multiplexing (OFDM)-based signals used to provide quintuple-play services along wavelength division multiplexing (WDM) long-reach passive optical networks (LR-PONs) is demonstrated experimentally. Particularly, the transmission performance of custom signal bearing Gigabit Ethernet data, Worldwide Interoperability for Microwave Access, Long Term Evolution and Ultra Wideband (sub-bands 2 and 3) signals is evaluated for different LR-PONs reaches, considering single-wavelength and WDM transmission, and using a centralized impairment compensation technique at the central office that is transparent to the services provided.

It is shown that error vector magnitude-compliant levels are obtained for all the OFDM-based signals in WDM LR-PONs reaching 100 km and that negligible inter-channel crosstalk is obtained for a channel spacing of 100 GHz regardless the OFDM-based signal considered. The successful multi-format OFDM transmission along the 100 km-long WDM LR-PON is achieved in the absence of optical dispersion compensation or single sideband modulation, and it is enabled by the performance improvement provided by the centralized impairment compensation realized.

OCIS codes: (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems.

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1. Introduction

The integration of wireless and optical access networks in a single hybrid network has been identified as a powerful solution to address the dramatic demand increase for high data-rate wireless connectivity experienced along the last years [1–3]. This integrated network provides high flexibility, large coverage area and high data-rates in a simple and cost-effective way. The full integration of the wireless and optical access networks can still be further exploited if

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the modulation formats of the signals used to transmit the wireless and wired services present similar features.

Nowadays, orthogonal frequency-division multiplexing (OFDM) is widely employed in wireless and wired networks [4–6]. The main advantages of OFDM-based signals are the tolerance to multi-path fading, robustness to intersymbol interference and flexible bandwidth allocation to provide multiple access inherent to multiband techniques [5–8]. Wireless OFDM is included in wireless local access networks (WLANs), ultra wideband (UWB), worldwide interoperability for microwave access (WiMAX) and long term evolution (LTE) standards, among others [5, 9–11]. The transmission of OFDM signals in optical fiber communication systems has been appointed for long-haul, metro and access networks [12–17].

Recently, the operational network requirements for the simultaneous transmission of quintuple-play services supported by OFDM-based signals along wavelength division multiplexing (WDM) long-reach passive optical networks (LR-PONs) have been discussed [3, 18]. Broadband wired Internet and phone/voice data, wireless high definition TV (HDTV), wireless (WiMAX, UWB and LTE) and home security/control services comprise the quintuple-play offered to the end users. An important advantage of this type of OFDM-based optical-wireless networks is the possibility to simultaneously compensate for the transmission impairments of all the transmitted signals [19]. This enables a centralized impairment compensation at the central office leading to reduced deployment cost, and operational and management network savings.

In this work, the simultaneous transmission of custom OFDM signal providing features similar to standard Gigabit Ethernet (GbE) (Internet and phone/voice data), LTE (wireless connectivity), WiMAX (wireless connectivity) and UWB (wireless HDTV) OFDM-based signals is experimentally demonstrated along WDM LR-PONs employing centralized impairment compensation at the central office and with reach of 100 km. Due to the particular features of the OFDM signals, such an integrated optical-wireless network allows for a cost-effective, fully centralized architecture where the transmission impairments compensation, and network management is performed only at the central office. The transmission impairments compensation is done by sounding the frequency response of the channel using a few RF-pilots inserted in the free band between the OFDM signals spectra. No further compensation, regeneration or format conversion is required along the network giving the streamlined network architecture capable of handling future services of interest.

2. Experimental setup

Figure 1 shows the diagram of the experimental setup deployed to emulate the OFDM-based quintuple-play services transmission along the WDM LR-PON employing centralized compensation. Figure 1 represents the downstream direction between the optical line termination (OLT) and the optical network unit (ONU). It should be understood as a particular case of the bi-directional WDM LR-PON proposed in [18] where different ONUs are served by different wavelengths in order to ensure that different contents may be delivered to different users without significant bandwidth requirements at the ONU side.

At the OLT, the custom OFDM signal bearing GbE data, and the wireless standard LTE, WiMAX and UWB OFDM-based signals are generated, multiplexed and passed by the centralized compensation block using off-line processing. Table 1 shows the parameters of the OFDM-GbE, LTE, WiMAX and UWB signals considered in this work. The multiplexed signal occupies the bandwidth between 1 GHz and 4.8 GHz. All the OFDM-based signals employ quadrature phase-shift keying mapping and, concerning UWB signals, only the second and third UWB sub-bands are transmitted as most of the UWB transceivers commercially available nowadays are operating only in the first three UWB sub-bands. The first UWB sub-band is

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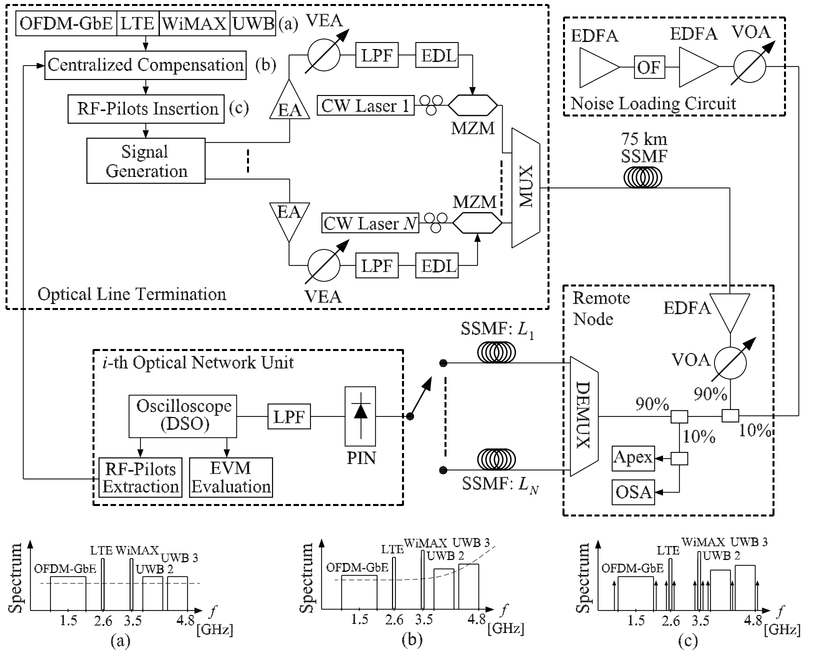

Apex: high resolution OSA	EDL: electrical delay line	OSA: optical spectrum analyzer
CW: continuous wave	EVM: error vector magnitude	PIN: positive-intrinsic-negative
DEMUX: demultiplexer	LPF: low-pass filter	RF: radio frequency
DSO: digital storage oscilloscope	MUX: multiplexer	SSMF: standard single-mode fiber
EA: electrical amplifier	MZM: Mach-Zehnder modulator	VEA: variable electrical attenuator
EDFA: erbium doped fiber amplifier	OF: optical filter	VOA: variable optical attenuator

Fig. 1. Experimental setup deployed to emulate the transmission of the OFDM-based signals along WDM LR-PONs employing centralized impairment compensation.

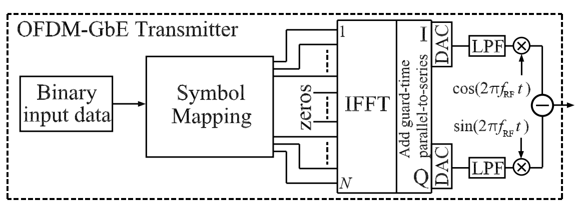

Fig. 2. Block diagram used to generate the custom OFDM-GbE signal. IFFT: inverse fast Fourier transform; DAC: digital-to-analogue converter; LPF: low-pass filter.

switched-off in order to avoid interference with the WiMAX signal according to current detect and avoid (DAA) regulation. The UWB, LTE and WiMAX signals are generated according to the corresponding standards [9–11]. The block diagram used to generate the OFDM-GbE signal is depicted in Fig. 2. The binary information is mapped onto the QPSK symbols and applied to the inverse fast Fourier transform (IFFT) block input together with a zero padding sequence. After the IFFT block and adding a guard-time, the OFDM symbols are converted to analogue signals using the digital-to-analogue converter (DAC). Then, the I and Q analogue components of the OFDM-GbE signal are filtered by ideal low-pass filters (LPF), with -3 dB bandwidth of

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Table 1. Parameters of the Custom 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]	1000	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	2048	256	128	128
Number of data subcarriers	81	1190	192	100	100
Number of pilot subcarriers	8	12	8	12	12
Number of guard subcarriers	39	846	56	16	16

500 MHz, to reduce the power of the high frequency aliasing components created by the DAC, and up-converted to the desired intermediate central frequency (1.5 GHz).

At the centralized compensation and RF-pilots insertion blocks, pre-distortion is applied to the multiplexed signal and the RF-pilots are inserted in the free band between the OFDM-based signals spectra. The operation principles of these two blocks are detailed in section 3. After the insertion of the RF-pilots, the electrical signal comprising the different OFDM-based services is generated by a Tektronix arbitrary waveform generator (AWG) in the interleaved mode and operating at 20 Gsamples/s. In order to adjust adequately the voltage level of the signal applied to the Mach-Zehnder modulator (MZM), an electrical amplifier (EA) and an variable electrical attenuator (VEA) are used. Before electro-optic conversion, the multiplexed signal is filtered by a LPF with -3 dB bandwidth of 8.15 GHz to reduce the electrical noise power reaching the MZM.

The electro-optic conversion is realized by chirpless 10 Gbit/s Sumitomo single arm MZMs biased at the quadrature point that are fed by continuous wave (CW) lasers. The different optical channels are multiplexed using a Gemfire 40-channel arrayed waveguide grating with 100 GHz of channel spacing. The average optical power levels at the input of the fiber spans are adjusted to ensure negligible degradation due to nonlinear fiber effects [20]. The reach of the first span (feeder fiber) of standard single-mode fiber (SSMF) is 75 km.

At the remote node (RN), the optical signal is amplified to compensate for the feeder fiber losses and combined with the amplified spontaneous emission noise (ASE) provided by the noise loading circuit. This circuit is used to adjust the optical signal-to-noise ratio (OSNR), defined in a reference bandwidth of 0.1 nm, to the desired value. The optical amplification was proposed to extend the reach of conventional PONs [21]. The different channels comprising the WDM signal are then demultiplexed using an arrayed waveguide grating identical to the one used at the OLT, and transmitted to the corresponding ONUs. The lengths of the RN-ONU spans (distribution fibers) analyzed in this work range between 0 and 50 km in order to emulate different distances between the RN and the users' premises.

At the ONU, the photodetection process is performed by a 10 GHz PIN with responsivity of 0.75 A/W. After photodetection, a LPF with -3 dB bandwidth of 4.85 GHz is used to reduce the power of high order distortion components and to avoid the generation of in-band distortion replicas due to the oscilloscope sampling process. The resulting signal is then digitized by an Agilent real time oscilloscope operating at 10 Gsamples/s and the different OFDM-based formats are off-line processed for demodulation. In the demodulation process, each OFDM signal is downconverted, applied to the fast-Fourier transform block and equalized. The equalizer transfer function for each OFDM signal is estimated from the information provided by

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the pilots' subcarriers. A regression method is implemented to estimate the equalizer transfer function along the band of the transmitted subcarriers.

Further information concerning the system parameters is provided in the following sections as they are slightly different from the single-wavelength to the WDM analysis realized in section 4.1 and 4.2, respectively.

3. Centralized compensation description

The basic idea of the centralized compensation approach is enabling the compensation of the transmission impairments induced along the WDM LR-PON at the OLT side. In addition, the centralized compensation should be transparent to the signals transmitted, i. e., the impairments should be suitably mitigated regardless the OFDM-based formats transmitted enabling future extension of the services provided by the operator in the same network.

The proposed centralized compensation approach is included into the pre-distortion methods group. However, rather than a conventional pre-distortion method where some training symbols are firstly transmitted or the pilots subcarriers of the OFDM signal are used to provide channel estimates, the proposed centralized compensation approach enables the estimation of the broadband channel without using the information of the pilots dedicated to each OFDM signal. This is of particular relevance for system operators as it enables the network upgrade by adding new OFDM-based signals without requiring significant modifications of the impairments compensation method employed.

The transmission of adaptively modulated optical OFDM (AMOOFDM) was proposed in the past to provide system capacity increase together with high tolerance to fibre transmission impairments [22, 23]. This is achieved by attributing different modulation formats (different number of bits per symbol) or power levels to the different subcarriers taking into account the frequency response of the transmission link and the signal-to-noise ratio (SNR) of each received OFDM subcarrier. In the case of the system proposed in this work, the modification of the modulation employed in each subcarrier of the OFDM wireless signals (UWB, LTE and WiMAX) is not possible for two reasons. First, that solution is not predicted in the standards. Second, in order to keep the ONU as cheaper as possible and to ensure network transparency, the information carried by the wireless signals is not accessible at the ONU: they are transmitted in their native format (without any modification of signal format) to the ONU side, where they are separated, amplified and radiated only.

In this work, the centralized compensation characteristic is estimated from the information provided by the RF-pilots inserted at the OLT side for broadband channel sounding. The RF-pilots are inserted close to the edges of the spectra of the different OFDM-based signals. These pilots are transmitted together with the multiplexed OFDM-based signal to the ONU and used for channel sounding. At the receiver side, the extraction block captures the amplitude information of the RF-pilots (although phase information can be also obtained, only amplitude information is used in this work as the phase compensation showed negligible additional advantage) and returns this information back to the OLT. From this information, the frequency response of the amplitude of the equivalent transfer function of the broadband channel is obtained for the RF-pilots frequencies and interpolated for the frequencies occupied by the different OFDM-based signals. From this frequency response, adequate pre-distortion is applied to the multiplexed signal in order to reduce the channel-induced degradations.

The proposed system uses the bidirectional OLT-ONU connectivity provided by the wired OFDM-GbE to transmit the information of the RF-pilots from the ONU to the OLT. The control plane included at the OLT for managing the transmission of the multi-format OFDM signals will also control the generation of the RF-pilots and configure the OFDM-GbE transceivers to include the information for channel estimation in the upstream direction. In this work, the

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RF-pilots information is obtained directly from the signal digitized by the oscilloscope and processed in Matlab to extract the channel response. This procedure was selected because this work is a preliminary proof-of-concept where only the downstream direction is considered and because the OFDM-GbE real-time transceivers are still being developed and are not available for the experiments.

Some of the benefits of the OLT centralized compensation approach are the low-complexity ONUs required and the provisioning of further services without requiring significant changes of the compensation approach, as the compensation is realized regardless the OFDM-based services provided. Additionally, as the equipments required to implement the centralized compensation approach are deployed at the OLT rather than at the ONU side, potential damaging of those equipments, caused by users' negligence, is also avoided.

The main challenge of the proposed centralized compensation approach is the complexity and cost of the equipment required to extract the RF-pilots information from the received signal. The immediate solution to extract the RF-pilots is digital signal processing after the digitization of the received signal by employing analogue-to-digital converters (ADCs) with adequate sampling frequency (10 Gsamples/s). Nowadays, this solution may be too expensive. Nevertheless, the electronics development in the near future can lead to substantial reduction of such equipments cost [15, 24].

Table 2 shows the frequency of the different RF-pilots inserted at the OLT for broadband channel sounding. Nine RF-pilots are used in this work (one close to each edge of the spectra of the different OFDM-based signals) and the pre-distortion response is evaluated from the RF-pilots information using a linear interpolation method.

Table 2. Frequency of the RF-Pilots Inserted at the OLT for Broadband Channel Sounding

Number of pilot	1	2	3	4	5	6	7	8	9
Frequency [GHz]	0.95	2.05	2.55	2.65	3.45	3.55	3.66	4.22	4.79

4. Experimental results and discussion

In this section, the performance of the different OFDM-based signals carried along the WDM LR-PON depicted in Fig. 1 and employing the centralized compensation described in section 3 is evaluated experimentally. Particularly, the error vector magnitude (EVM) of the different signals is evaluated for the following distances between the RN and the ONU: 0 km, 10 km, 25 km, 35 km and 50 km. These RN-ONU distances correspond to OLT-ONU reaches of 75 km, 85 km, 100 km, 110 km and 125 km, respectively. The EVM obtained in back-to-back operation is also evaluated as a reference.

The wireless transmission of LTE, WiMAX and UWB signals at the users' premises was not considered in the experiments. The goal of this work is to verify if the quality of the bundle of OFDM-signals coexisting in the WDM LR-PON after optical transmission along the integrated wired-wireless network is still acceptable. As the EVM limits of the current standards, considered in this work as a reference, are defined at the output of the wireless transmitter antenna to ensure that the quality of the signal before the wireless transmission is enough to establish the wireless link, the goal is achieved by guarantying that the EVM of the different signals at the output of the optical fiber link is compliant with the EVM limits of the corresponding standard. The EVM limits of the different wireless services are: -14.5 dB for UWB [9], -15.1 dB for LTE [10] and -20 dB for WiMAX [11]. The EVM limit of the OFDM-GbE signal is -11 dB (corresponding to BER$\approx 10^{-4}$ in a noise-impaired system). The EVM is evaluated

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from the symbols carried by the subcarriers of 20 LTE symbols, 100 WiMAX symbols, 1340 OFDM-GbE symbols and 1140 UWB symbols. The reason for different number of symbols is the different duration of the OFDM symbol of each signal (see Table 1).

The results are obtained considering the modulation index of the voltage signal applied to the MZM arm (defined as $m = V_{RMS}/V_x$ where V_{RMS} is the root-mean-square voltage of the multiplexed signal applied to the MZM arm and V_x is the switching voltage of the MZM) set to 9%. This modulation index corresponds to a good compromise between SNR and signal distortion caused by the system nonlinearities for the different OFDM-based signals [25]. The power of the multiplexed signal before the pre-distortion is equally shared by the different OFDM-based signals. This power division may not correspond to the optimum system operation. Nevertheless, the centralized compensation approach is able of coarse tuning the power distribution between the different signals in a simple and adaptive way.

4.1. Single-wavelength transmission

In this sub-section, the transmission performance of the OFDM-based signals along the LR-PON using only a single optical channel is assessed. The CW laser is a Fabry Perot HP 8168F tunable laser operating at 193.1 THz and with a laser linewidth of 100 kHz. The average optical power level of the signal launched into the feeder and distribution fibers is -6 dBm and 1 dBm, respectively. The OSNR is set to 30 dB.

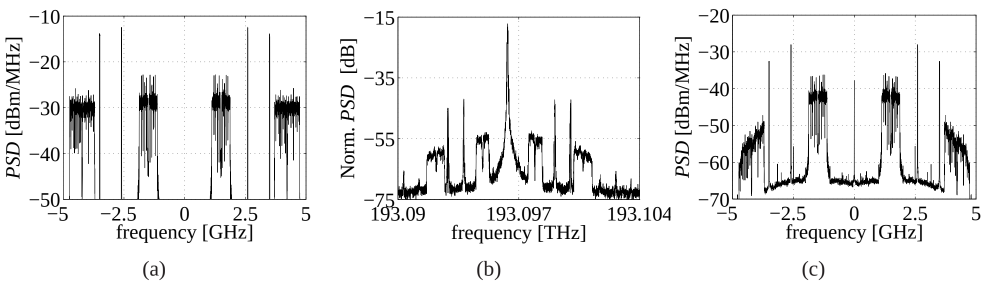

Fig. 3. Measured spectra of the signal at different points of the experimental setup: a) at signal generator output, b) at DEMUX input and c) at the receiver LPF output. The total LR-PON reach is 110 km and no centralized compensation is employed.

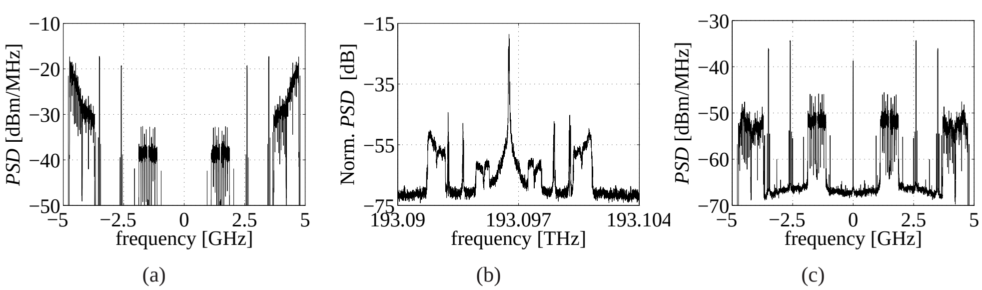

Fig. 4. Measured spectra of the signal at different points of the experimental setup: a) at signal generator output, b) at DEMUX input and c) at the receiver LPF output. The total LR-PON reach is 110 km and the centralized compensation described in section 3 is employed.

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Figures 3 and 4 depict the power spectral densities (PSDs) of the OFDM-based signals at different points of the experimental setup. Results obtained with and without centralized compensation are presented and a LR-PON distance of 110 km is considered. Figure 3(a) shows that the spectrum of the signal applied to the MZM is composed by the UWB bands 2 and 3, LTE, WiMAX and OFDM-GbE signals. The inspection of Fig. 3(a) shows that the difference between the peak PSD of the OFDM-GbE (signal with lower central frequency) and the peak PSD of the UWB sub-band 3 (signal with higher central frequency) is around 3 dB. Figure 3(b) indicates that, at the input of the DEMUX installed at the RN, this peak PSD difference reaches 6 dB. This is mainly due to the attenuation introduced by the frequency response of the devices of the transmitter (AWG, electrical amplifiers, MZM). At the electrical receiver side, the PSDs difference is 14 dB due to the dispersion-induced power fading [26], and the attenuation introduced by the PIN and the LPF (see Fig. 3(c)). In order to overcome this power limitation, the centralized compensation attributes higher gain to the signals located at higher frequencies at the expense (to keep the modulation index of the signal applied to the MZM in 9%) of power reduction of the signals transmitted at lower frequencies, as shown in Fig. 4(a). With this approach, the power sharing between the different OFDM-based signals at the ONU side when the centralized compensation is employed is similar to the power sharing of the signals prior applying the pre-distortion. The inspection of Fig. 4(c) shows that the difference between the peak PSDs of the OFDM-GbE signal and UWB sub-band 3 at the electrical receiver side when centralized compensation is used, is around 3 dB.

Figure 5 depicts the EVM of the UWB sub-bands 2 and 3, LTE, WiMAX and OFDM-GbE signals as a function of the different OLT-ONU distances under analysis. Results obtained with and without applying centralized compensation are presented. The EVM obtained in back-to-back operation and with centralized compensation is also shown as a reference. The inspection of Fig. 5 clearly shows the main advantage of the centralized compensation approach proposed: it enables achieving EVM-compliant levels in all the OFDM-based signals for LR-PONs comprising OLT-ONU distances up to 110 km whereas, in the absence of the proposed centralized compensation approach, only 85 km are reached. Additionally, Fig. 5 shows also that: i) an EVM improvement exceeding 5 dB is achieved in the UWB sub-band 3 when the centralized compensation is used, ii) the EVM of LTE, WiMAX and UWB sub-band 2 does not show significant variations when compared with the case where no centralized compensation is considered, and iii) a significant EVM degradation of OFDM-GbE that may exceed 6 dB is observed with centralized compensation.

The EVM improvement of the UWB sub-band 3 and the EVM degradation of OFDM-GbE are directly related. From Fig. 3(c), the power of the received OFDM-based signals at higher central frequencies is lower than the one of the signals received at lower frequencies in the absence of centralized compensation. This power reduction is detected by the centralized compensation approach using the RF-pilots information and, to counteract such degradation effect, a pre-distortion response covering the whole band of all OFDM-based signals, with high gain at higher frequencies, is generated (see Fig. 4(a)). If the power of the signals located at higher frequencies (e. g., UWB sub-bands 2 and 3) increases, the voltage level of the multiplexed signal applied to the MZM will also increase and a modulation index higher than 9% (the modulation index employed in the absence of centralized compensation) is obtained. In order to keep the same system conditions with and without centralized compensation, the multiplexed signal must be properly attenuated by the VEA prior to be applied to the MZM. As a consequence, the power increase of the signals at higher frequencies is accompanied by a power decrease of the lower frequency signals (compare the PSD of the different OFDM signals in Fig. 3(a) and in Fig. 4(a)), with the corresponding EVM degradation. As the OFDM signals at higher central frequencies are the ones showing stronger EVM limitations (see in Fig. 5, the EVM of

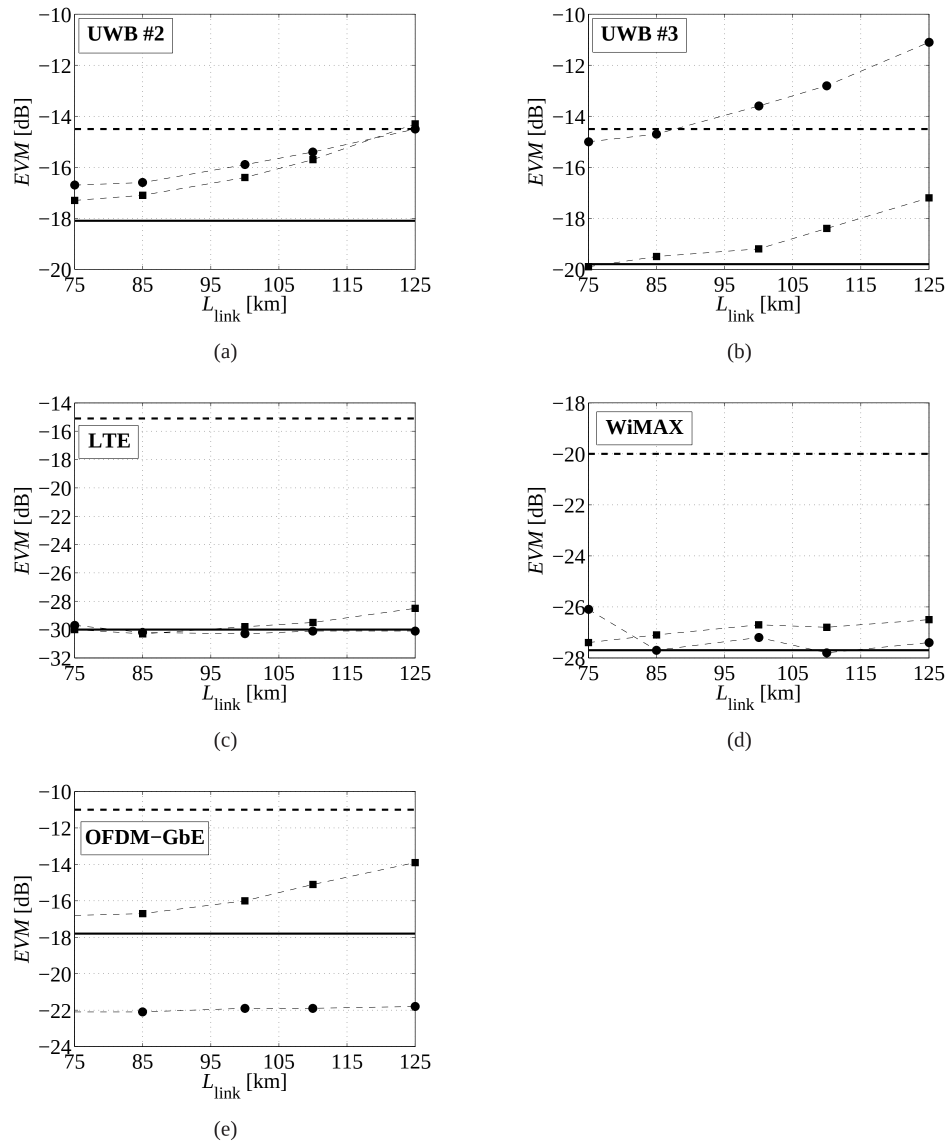

Fig. 5. EVM of the different OFDM-based signals as a function of the reach of the LR-PON. Results obtained without centralized compensation (circles) and with centralized compensation (squares). EVM limit of each OFDM-based signal (dashed lines). EVM obtained in optical back-to-back operation with centralized compensation (continuous lines).

UWB sub-bands), it is concluded that the centralized compensation provides an adaptive power transfer from the most EVM-relaxed to the most EVM-constrained signals.

Figure 5 shows that, when the centralized compensation is employed, the most restrictive signal is the UWB sub-band 2. Figure 5 shows also that, taking into account the different OLT-ONU distances under analysis in this work, EVM-compliant values are obtained in UWB sub-band 2 for LR-PON reaches up to 110 km, whereas EVM levels above the limit are observed for a LR-PON reach of 125 km. Hence, for the distances tested, the transmission of the multi-

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format OFDM-based signals achieves EVM-compliant levels only up to OLT-ONU distances of 110 km.

The inspection of Fig. 5 indicates that, for the LR-PONs distances analyzed, the LTE and WiMAX signals present an EVM degradation relative to back-to-back operation lower than 2 dB. On other hand, the EVM degradation of UWB sub-band 2 achieves almost 4 dB for an OLT-ONU distance of 125 km. In the case of UWB sub-band 3, the EVM degradation obtained when no compensation is employed is 5 dB and 9 dB for OLT-ONU distances of 75 km and 125 km, respectively. However, when the centralized compensation is used, a negligible EVM degradation relative to back-to-back operation is obtained for an OLT-ONU distance of 75 km and an EVM degradation not exceeding 3 dB is achieved for an OLT-ONU distance of 125 km. This lower EVM degradation relative to back-to-back operation observed in UWB sub-band 3 is because the centralized compensation attributes more power to that signal at the OLT side and, as a consequence, the SNR of the signal at the ONU side improves considerably. Contrarily, Fig. 5(e) shows that the EVM of OFDM-GbE signal when no centralized compensation is employed is 4 dB below the EVM obtained in back-to-back operation. This is due to the following two aspects: (i) the back-to-back results were obtained with centralized compensation (only the attenuation of the amplitude response of the system, for high frequencies, is compensated for in that case), and (ii) due to the higher attenuation suffered by UWB signals, the centralized compensation attributes more power to these signals at the expense of the reduction of the power of the signals located at lower frequencies (for instance, OFDM-GbE) with the consequent EVM degradation. Figure 5(e) shows also that although a negligible EVM variation is obtained along the range of OLT-ONU distances analyzed when no compensation is accomplished, a significant EVM degradation (exceeds 2 dB for an OLT-ONU distance of 125 km) is observed with the increase of the LR-PON reach when the centralized compensation is used. This is due to the influence of the dispersion-induced power fading: as the power fading degradation increases considerably with the accumulated dispersion and signal frequency increase, as far as longer OLT-ONU reaches are considered higher power levels are attributed by the centralized compensation to the signals at higher frequencies and, to keep the modulation index unchanged, lower power levels are attributed to the signals at lower frequencies. As a consequence, a lower SNR in those signals at the ONU side is observed with the corresponding EVM degradation.

4.2. WDM transmission

In this sub-section, the transmission of the OFDM-based signals along a WDM LR-PON employing three optical channels and centralized compensation is demonstrated experimentally. The CW light signals used to feed the chirpless MZMs are provided by two distributed feedback JDSU lasers operating at 193.1 THz and 193.2 THz (linewidths of the order of 10 MHz), and the tunable HP 8168F Fabry Perot laser operating at 193.0 THz (linewidth of 100 kHz). The average optical power of the WDM signal launched into the feeder and distribution fibers is -1 dBm.

The target OSNR for each of the three optical channels is 30 dB. However, slight OSNR fluctuations, not exceeding 0.6 dB, were observed between the channels. The WDM LR-PON operation is as follows: the channel at 193.0 THz is used to deliver the OFDM-based services to ONU 1 (installed at 75 km far away from the OLT), the channel at 193.1 THz is used to deliver the OFDM-based services to ONU 2 (installed at 100 km far away from the OLT) and the channel at 193.2 THz serves ONU 3 (installed at 85 km far away from the OLT). In this way, the center channel of the WDM signal (the one that may suffer from stronger inter-channel crosstalk) is serving the ONU farther away from the OLT in order to emulate a worst case scenario.

Due to the limited number of independent AWG outputs, the following procedure is used to

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evaluate the performance of the WDM LR-PON:

1. The multiplexed electrical signal comprising the OFDM-GbE, LTE, WiMAX and UWB sub-bands is obtained from the single output channel of the AWG.
2. The electrical signal is split into three signals using power dividers and decorrelated using electrical delay lines (EDLs).
3. Each one of the three electrical signals modulate the three optical channels with the RF-pilots inserted but in the absence of pre-distortion.
4. After transmission, the optical channel corresponding to the ONU under analysis is photodetected and digitized.
5. The channel estimation corresponding to the path between the OLT and the desired ONU is obtained from the RF-pilots information extracted from the digitized waveform. The corresponding pre-distortion is applied to the electrical multiplexed signal at the OLT side using off-line processing.
6. The pre-distorted multiplexed electrical signal is obtained from the single output channel of the AWG and the three electrical signals are obtained using the power dividers and the EDLs.
7. Each one of the three electrical signals modulate the three optical channels with the RF-pilots inserted.
8. After transmission, the optical channel corresponding to the ONU under analysis is photodetected, digitized and the performance of the different OFDM-based services is evaluated.
9. The procedure returns to the first point in order to evaluate the performance of the OFDM-based services delivered to other ONU (or, equivalently, transmitted in other optical channel).

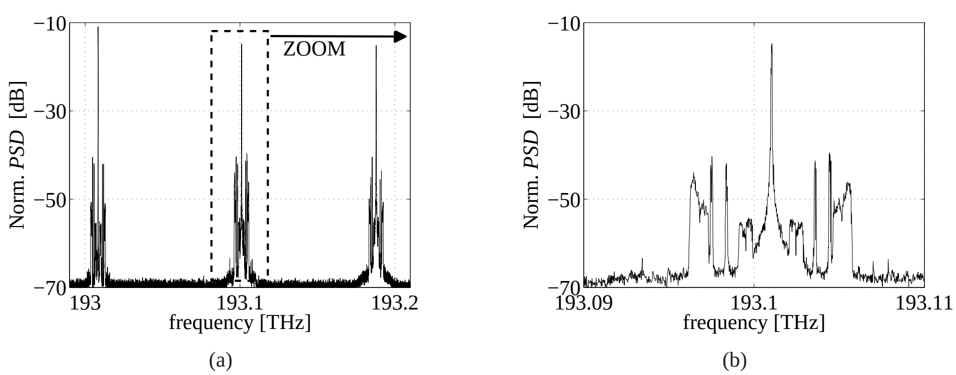

Fig. 6. (a) Measured spectrum of the WDM signal at the input of the DEMUX installed at the RN. (b) Zoom of the central channel of the WDM signal shown in (a). The pre-compensation applied to each signal at the OLT side is the result of the channel estimation obtained for an OLT-ONU distance of 100 km.

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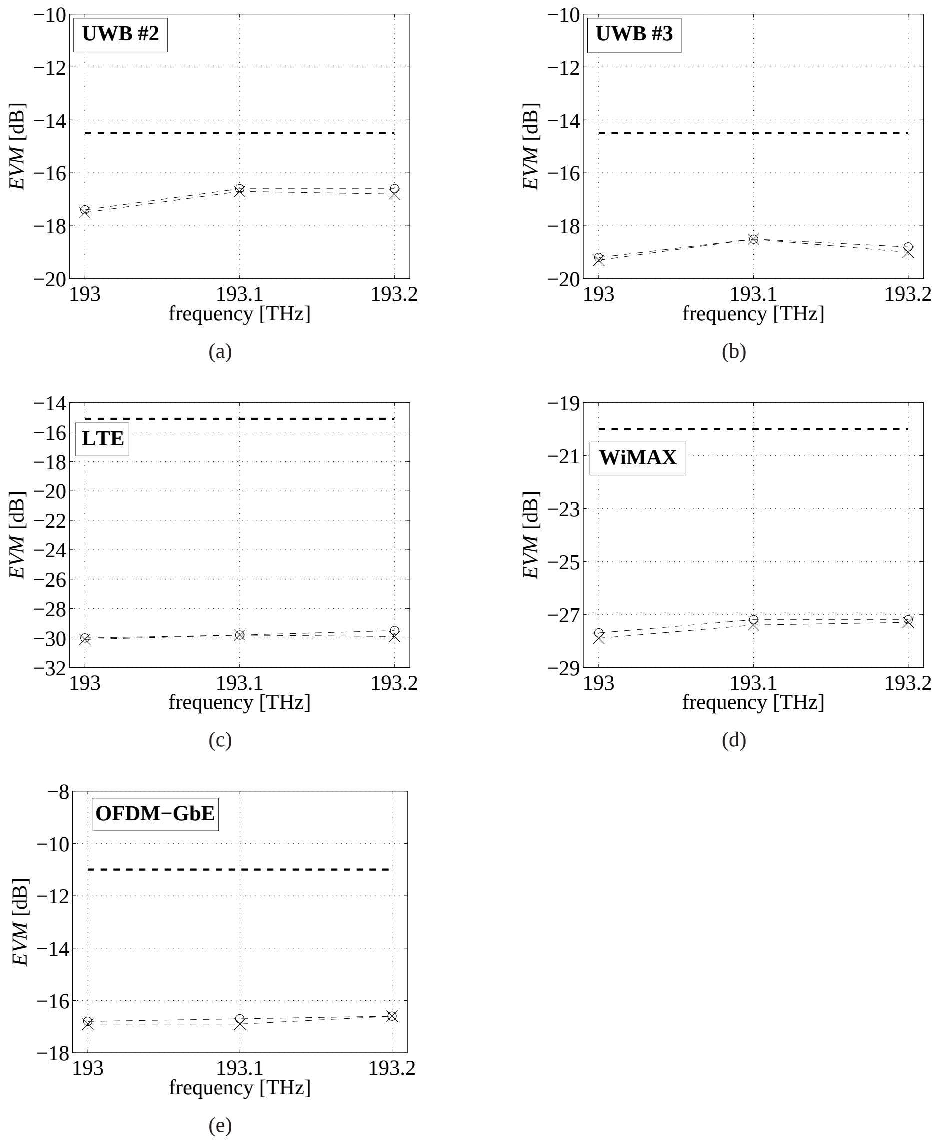

Fig. 7. EVM of the different OFDM-based signals transmitted in the WDM LR-PON employing three optical channels. Results obtained for ONU 1, ONU 2 and ONU 3 served by the channel centered at 193.0 THz, 193.1 THz and 193.2 THz, respectively (circles). EVM obtained in each optical channel in single-wavelength operation (crosses). EVM limit of each OFDM-based signal (dashed lines). Centralized compensation is employed.

In the procedure aforementioned, the main drawback associated with the limited number of independent AWG outputs is that the performance of the pre-distorted OFDM-based signals supported by a given optical channel is evaluated with the other two optical channels supporting OFDM-based signals with identical pre-distortion features. Nevertheless, it is expected that the referred implementation constraint does not affect the conclusions drawn.

Figure 6 depicts the PSD (measured from the APEX optical spectrum analyzer with a resolu-

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tion of 0.16 pm) of the WDM signal at the input of the DEMUX installed at the RN. Figure 6(b) shows a zoom of the central channel of the WDM signal presented in Fig. 6(a). Figure 6 shows that there is not spectral overlapping between adjacent channels as the spectrum of the signals transmitted in each wavelength are compacted.

Figure 7 shows the EVM of the different OFDM-based signals transmitted in the three optical channels of the WDM signal when centralized compensation is employed. EVM results obtained when each one of the three optical channels is transmitted individually (the remaining channels are switched-off) are also presented as a reference. The inspection of Fig. 7 shows that the performance of the different OFDM-based signals carried by the three optical channels is similar (the EVM variation of each service along the three channels does not exceed 1 dB) and that all the signals present EVM-compliant levels. The EVM variation not exceeding 1 dB is in agreement with the EVM results shown in Fig. 5. Additionally, the comparison between the results obtained when the three optical channels are transmitted simultaneously and the single-wavelength situation allows concluding that the inter-channel crosstalk is negligible. This conclusion is supported by the reduced EVM degradation observed: although a maximum EVM degradation of 0.4 dB is observed in the LTE signal transmitted at the channel located at 193.2 THz, the EVM degradation obtained in all the other signals is lower than 0.2 dB. These residual different EVM degradations may be attributed to the slight OSNR fluctuations observed along the experiments and also to the very low (and, thus, very sensitive) EVM levels measured in LTE signals.

5. Conclusion

The performance of the simultaneous distribution of OFDM-based quintuple-play services along distances indicated for LR-PONs has been assessed experimentally. Single-wavelength and multi-wavelength transmission studies have been performed and a service-transparent centralized impairment compensation using broadband channel sounding has been employed.

It has been shown that the centralized compensation approach enables achieving EVM-compliant levels in all the OFDM-based signals for WDM LR-PONs comprising OLT-ONU distances up to 100 km, and employing three 100 GHz spaced channels. The experimental results have shown also that, for a channel spacing of 100 GHz, negligible crosstalk between the WDM channels is achieved as an EVM degradation due to the WDM transmission not exceeding 0.4 dB is observed regardless the OFDM signal format.

The study performed in single-wavelength transmission has shown that EVM improvements of 6 dB are achieved in the most performance-constrained OFDM signals due to the centralized impairment compensation employed at the central office. These EVM improvements are achieved at the expense of power reduction of the OFDM signals showing better performance when no impairment compensation is realized. Hence, the centralized compensation can be viewed as a low-complexity and adaptive method that automatically adjusts the relation between the power of the different OFDM-based signals taking into account the different channel impairments.

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