Experimental Distribution of OFDM-UWB Radio Signals along Directly Modulated Long-reach Pons Indicated for Sparse Geographical Areas

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Keywords: Long-Reach Passive Optical Networks, Orthogonal Frequency-Division Multiplexing, Ultra Wideband, Directly Modulated Lasers, Optical Dispersion Compensation.

Abstract: The distribution of three orthogonal frequency division multiplexing (OFDM) ultra wideband (UWB) bands along directly modulated long-reach (LR) passive optical networks (PONs) is demonstrated experimentally. Adequate selection of the UWB signal applied to the directly modulated laser (DML) and fixed in-line optical dispersion compensation are shown as effective solutions to reach 130 km of standard single-mode fibre. In addition, error vector magnitude (EVM) levels compliant with the UWB standard are achieved for LR-PONs with reaches between 75 km and 130 km. It is also shown that, for optical channel spacing as narrow as 0.2 nm, the proposed system suffers from negligible linear inter-channel crosstalk as the EVM of the UWB bands transmitted in the central channel of a wavelength division multiplexing (WDM) signal consisting in three optical channels, is similar to the EVM of the UWB bands transmitted in that channel when single-channel operation is considered. These results demonstrate that the proposed directly modulated LR-PON is an adequate solution to deliver the UWB signals to users' premises located in sparse take-up geographies.

1 INTRODUCTION

Ultra wideband (UWB) radio communication systems have been receiving a special attention over the last years. Such systems can benefit from several UWB advantages as high data rate broadcasting (480 Mbits/s (Staccato Communications, 2005); (ITU-R, 2004), tolerance to multi-path fading, possibility of co-existence with other already employed technologies (IEEE 802.11 and IEEE 802.16), position monitoring and low power consumption allowing small size/low cost integration (Siriwongpairat and Liu, 2008).

UWB is an unlicensed technology that uses radio modulation techniques with a minimum bandwidth of 500 MHz or at least 20% greater than the centre frequency of operation. UWB channels must be allocated in the band between 3.1 and 10.6 GHz with a maximum equivalent isotropic radiated power (EIRP) of -41.3 dBm/MHz (EU, 2007); (FCC, 2002). The UWB radio signals broadcasting is indicated for small environments like homes and offices premises. Impulse-radio (IR) and orthogonal frequency division multiplexing (OFDM) were proposed as UWB signal modulation formats (Siriwongpairat and Liu, 2008). The OFDM-UWB solution has shown enhanced features such as higher flexibility to provide multiple access inherent to multi-band techniques, tolerance to multi-path fading and intersymbol interference (ISI), and reduced band limitations in the UWB transceiver due to the 528-MHz-wide channelization of OFDM-UWB signals rather than 7.5 GHz of bandwidth for IR-UWB signals. Furthermore, devices for OFDM modulation and demodulation are already available due to the use of OFDM in other wireless applications like IEEE 802.11 and IEEE 802.16. Hence, this work is focused only on OFDM-UWB radio signals.

Significant efforts from microelectronic companies developing UWB terminals and devices at low cost have been accomplished in order to reach a large scale penetration of the UWB technology in the access telecommunication networks (UROOF, 2005). The Wimedia Alliance, a non-profit

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DOI: 10.5220/0004615104120418
In *Proceedings of the 4th International Conference on Data Communication Networking, 10th International Conference on e-Business and 4th International Conference on Optical Communication Systems* (OPTICS-2013), pages 412-418
ISBN: 978-989-8565-72-3

organization that defines, certifies and supports enabling wireless technology for multimedia applications, defined data rates up to 1 Gbit/s and the creation of a global UWB radio standard with guaranteed inter-operability as main targets for the UWB radio specifications. Hence, UWB technology presents the advantage of broadcasting higher data rate between electronic devices than traditional communications and it is indicated to be used by high quality multimedia equipment as personal digital video recorders (DVR), high definition television (HDTV), laptops and cable/satellite set-top boxes (ITU-R, 2004); (Wimedia, 2013).

The transmission of UWB radio signals along optical fibre in short-range environments was already investigated (Guo et al., 2007). The application target of such investigation is to cover buildings/offices with an integrated optical fibre distribution/wireless broadcasting solution that allows the end-users to benefit from the high mobility and high bit-rate over short ranges capabilities provided by the UWB-based wireless networks. The transmission of these UWB radio signals over fibre-to-the-home (FTTH) infrastructures is a powerful solution to address the distribution of UWB signals along longer distances. Moreover, avoiding trans-modulation or frequency conversion of the UWB radio signals at the end-users' premises, the subscribers can benefit from low cost transponders and a deep penetration can be expected worldwide. The considered FTTH paths correspond to standard lengths used in passive optical networks (PONs) to connect distribution hubs (DH) to UWB end users (up to 60 km).

Recently, the increase of the reach of the FTTH paths has been a hot research topic supported by the operators' point of view (Davey et al., 2009). The main target of this topic is to reach 100 km between the central office and the users' premises, and it is indicated for the metro and access networks integration envisaged by long-reach (LR) PONs (Davey et al., 2009). In LR-PONs, the optical line termination (OLT) at the central office (CO) is connected to an active remote node (RN) via a fibre span denominated feeder or trunk line (Davey et al., 2009). The target reach of this span is around 80 km and optical amplification is performed at the RN in order to compensate for the losses introduced along the optical link. The different optical network units (ONUs) are then connected to the RN via a completely PON with reach around 20-30 km. From the operators' viewpoint, some of the benefits of the LR-PONs are (Davey et al., 2009): i) decrease the number of OLTs deployed and provide a full integration between the metro and access networks with the corresponding system cost savings, ii) sharing the OLT and the feeder fibre by several users in a sparse take-up geography and iii) decrease the configuration and management issues of the network.

External and direct modulation have been recently proposed and demonstrated as effective solutions to be employed in LR-PONs supporting radio-over-fibre signals (Alves et al., 2013). External modulated LR-PONs have shown better performance, whereas directly modulated LR-PONs are viewed as a cost-effective and alternative solution. However, the maximum reach of directly modulated LR-PONs is commonly assumed shorter than when external modulation is employed due to the combined effect of the chirp introduced by the directly modulated laser (DML) and the fibre dispersion.

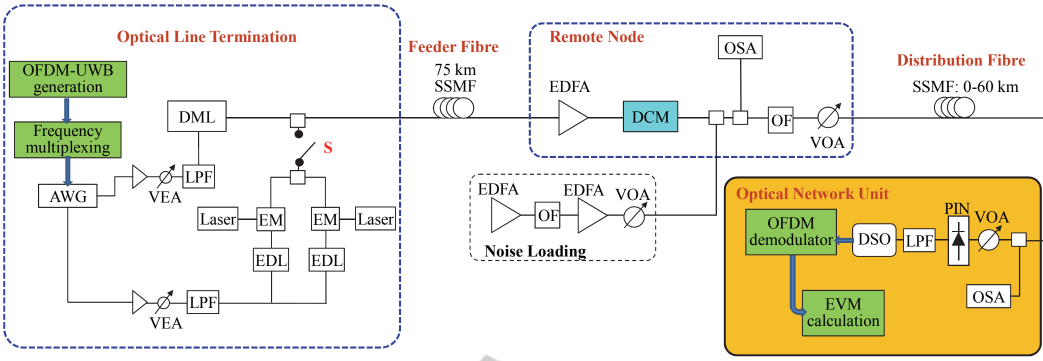
The study of the directly modulated LR-PON work proposed in (Alves et al., 2013) for the provisioning of different wired and wireless OFDM-based services to the end users showed that the performance of the bundle of OFDM signals is impaired mainly by the UWB signals. This is due to the higher bandwidth of UWB signals and also due to their higher central frequencies (Alves et al., 2013).

In this work, we focus our attention only in the transmission of the UWB signals along directly modulated LR-PONs. Particularly, we propose and demonstrate experimentally useful system design guidelines enabling the distribution of UWB signals along directly modulated LR-PONs with maximum reach exceeding 100 km. This directly modulated extended LR-PON is a powerful solution to distribute the UWB signals to users' premises located at sparse geographical areas in a cost-effective manner.

2 EXPERIMENTAL SETUP

Figure 1 depicts the diagram of the experimental setup employed to assess the performance of the OFDM-UWB signals distribution along the directly modulated LR-PON. Figure 1 depicts a multi-wavelength setup comprising three optical channels. However, in this section, we focus the system description only on the single-channel operation, i. e., the switch S presented in Figure 1 is in the open position. Further information about the multi-wavelength setup is provided in section 3.2.

The OFDM-UWB bands #1, #2 and #3 are generated and frequency multiplexed through digital



AWG: arbitrary waveform generator	LPF: low-pass filter
DCM: dispersion compensation module	OF: optical filter
DML: directly modulated laser	OFDM: orthogonal frequency-division multiplexing
DSO: digital storage oscilloscope	OSA: optical spectrum analyzer
EA: electrical amplifier	PIN: positive-intrinsic-negative
EDFA: erbium doped fiber amplifier	SSMF: standard single-mode fibre
EDL: electrical delay line	UWB: ultra wideband
EM: external modulator	VEA: variable electrical attenuator
EVM: error vector magnitude	VOA: variable optical attenuator

Figure 1: Schematic diagram of the experimental setup implemented in the laboratory to emulate the distribution of the UWB signals along a directly modulated LR-PON.

signal processing (DSP) in Matlab. The raw data rate of each UWB band is 320 Mbaud and the UWB bands #1, #2 and #3 are centred at the frequencies of 3.4 GHz, 3.9 GHz and 4.4 GHz, respectively, and each UWB band occupies a bandwidth of 528 MHz. Hence, after multiplexing, the spectral occupancy of the three UWB bands is between 3.1 GHz and 4.7 GHz. Quadrature phase-shift keying (QPSK) mapping and similar power levels between the three OFDM-UWB bands are considered. Only these three bands are considered in these experiments because most of the UWB devices commercially available nowadays operate only in these UWB bands and also due to the limited bandwidth of the DML available in the laboratory. The electrical signal is generated by an arbitrary waveform generator operating at 20 Gsamples/s. A radio frequency (RF) amplifier and a variable electrical attenuator are used to set the modulation index of the signal applied to the DML. After amplification, the electrical noise power is reduced by using a low-pass filter (LPF) with -3 dB bandwidth of 7.6 GHz. The DML is a low-cost multi-quantum well DFB laser characterized by a threshold current of I_{th}=8.1 mA, a bias current of I_b=30 mA, a chirp parameter of 2.6, nominal wavelength of 1552.85 nm and an intensity response bandwidth of about 4 GHz (Morgado et al., 2011).

The OFDM-UWB signal is launched into a 75 km-long feeder standard single-mode fibre (SSMF), with dispersion parameter of 17 ps/nm/km, with an average optical power of 0 dBm.

At the remote node (RN), an optical amplifier compensates for the fibre loss and a dispersion compensating module (DCM) is used to reduce the degradation induced by the combined effect of the DML's chirp and the fibre dispersion. A noise loading circuit is used to set the optical signal-to-noise ratio, in a 0.1 nm bandwidth, to 30 dB. The amplified spontaneous emission noise power is reduced by using an optical filter with -3 dB bandwidth of 16 GHz. The average optical power at the input of the distribution fibre is also 0 dBm.

Different distribution fibre reaches are considered along the study in order to measure the performance of the OFDM-UWB signals distribution for different LR-PON distances. Particularly, distribution fibres with reach between 0 km and 60 km are analysed. These distribution fibre reaches correspond to LR-PON with reaches between 75 km and 135 km.

At the ONU, the average optical power at the photodetector input is set to -12.5 dBm. The signal is photodetected by a 10 GHz PIN including a transimpedance amplifier stage. After photodetection, the UWB signal is filtered by a LPF with -3 dB bandwidth of 10 GHz and sampled by a real-time oscilloscope operating at 20 Gsamples/s. DSP algorithms are then applied to the sampled signal waveform in order to demodulate each OFDM-UWB band. These algorithms comprise RF carrier recovery, time synchronization, down-conversion, ideal filtering, FFT window synchronization, common phase error compensation and equalization. After DSP, the EVM of each received OFDM-UWB band is evaluated and compared with the EVM limit

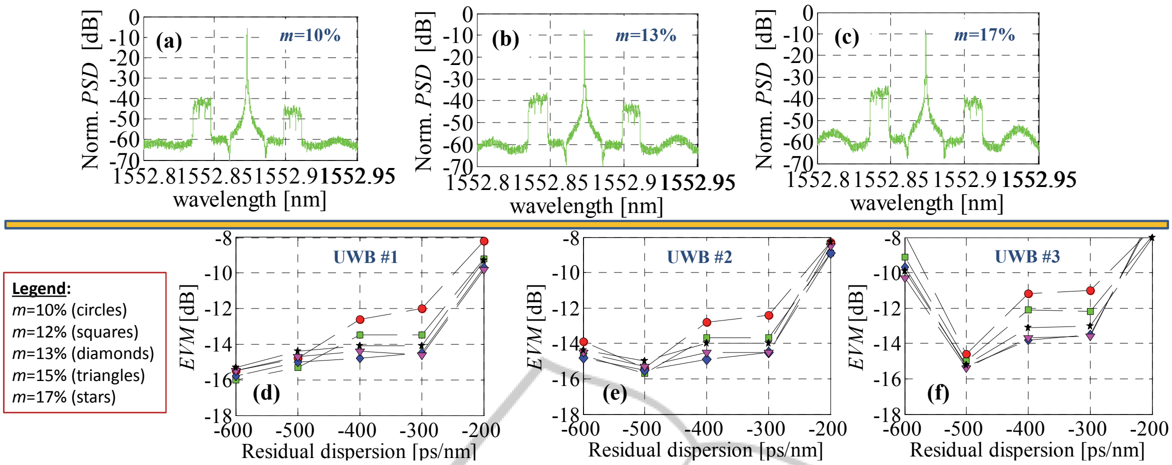


Figure 2: (a), (b) and (c) PSD of the signal after the DCM inserted at the RN for different modulation indexes. (d), (e) and (f) EVM of UWB band #1, #2 and #3 as a function of the residual dispersion of the link and for different modulation indexes. In (d), (e) and (f), the LR-PON reach is 100 km and *m*=10% (circles), *m*=12% (squares), *m*=13% (diamonds), *m*=15% (triangles), *m*=17% (stars).

(-14.5 dB for QPSK) of UWB standard (ECMA Int., 2007). The EVM limit of UWB standard is defined at the output of the wireless transmitter, i. e., before wireless radiation. Therefore, it can be used as performance threshold of the UWB signals at the output of optical fibre link.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Single-wavelength Operation

In this section, the EVM of each of the three OFDM-UWB bands simultaneously distributed along the LR-PON infrastructure described in section 2 is evaluated experimentally and discussed.

Initially, the optimization of the modulation index of the OFDM-UWB signal applied to the DML (in order to optimize the level of nonlinear distortion induced by the combined effect of the DML and the PIN) and of the optical dispersion compensation level of the DCM (to minimize the degradation due to the joint effect of DML's chirp and fibre dispersion) located at the RN is performed. The optimization outcomes depend on the reach of the LR-PON considered due to the interaction between the accumulated dispersion of the link and the chirp introduced by the DML. Thus, we decided to perform the optimization for a RN-ONU distance of 25 km (total LR-PON reach of 100 km). The system optimization is accomplished for this reach as it represents a compromise between two LR-PON reaches. First, we want to ensure the distribution of UWB signals along a minimum LR-PON reach (the feeder fibre length, 75 km) with acceptable performance. Second, we want to extend the maximum LR-PON reach for a distance longer than 100 km while keeping the reception of UWB signals with acceptable conditions.

The modulation index is defined as $m = V_{RMS} / \left[\left(I_b - I_{th} \right) \times R_L \right]$, where V_{RMS} is the root mean square (RMS) voltage of the OFDM-UWB signal applied to the DML and R_L is the load resistance ($R_L = 50\ \Omega$).

Figures 2 (a), (b) and (c) depict the PSD of the optical signal at the RN for different modulation indexes levels. Figures 2 (a), (b) and (c) show that the modulation index increase leads not only to the power increase of the UWB bands but also to the power increase of the distortion components generated due to the nonlinear characteristic of the DML.

Figures 2 (d), (e) and (f) show the EVM of each OFDM-UWB band as a function of the residual dispersion (defined as the difference between the accumulated dispersion of the feeder and distribution fibres, and the dispersion compensated by the DCM) of the link. The EVM results are presented for different modulation indexes. Figures 2 (d), (e) and (f) show that the behaviour of the EVM when the residual dispersion varies depends on the UWB band under analysis. Particularly, the inspection of Figures 2 (d), (e) and (f) show that the tolerance of the EVM to negative residual dispersion levels decreases when the number of the UWB band increases, i. e., when the central frequency of the UWB band increases. This effect occurs because the intensity response of the link is remarkably affected by the residual dispersion. Further investigation showed that, if the residual dispersion of the link changes from -300 ps/nm (DCM adjusted to compensate for 2000 ps/nm of dispersion) to -600 ps/nm (DCM adjusted to compensate 2300 ps/nm), an amplitude gain close to 9 dB occurs at the frequency of 3.4 GHz (central frequency of UWB band #1). However, this gain is reduced to 5 dB at the frequency of 4.4 GHz (central frequency of UWB band #3).

On the other hand, Figures 2 (d), (e) and (f) show also that the performance of the UWB bands is remarkably dependent on the modulation index. For low modulation indexes, the EVM improves when the modulation index increases due to the improvement of the signal-to-noise ratio. However, for high modulation indexes, this EVM improvement is counterbalanced by the degradation induced by the nonlinear distortion caused by the DML nonlinear characteristic and the PIN square law detection.

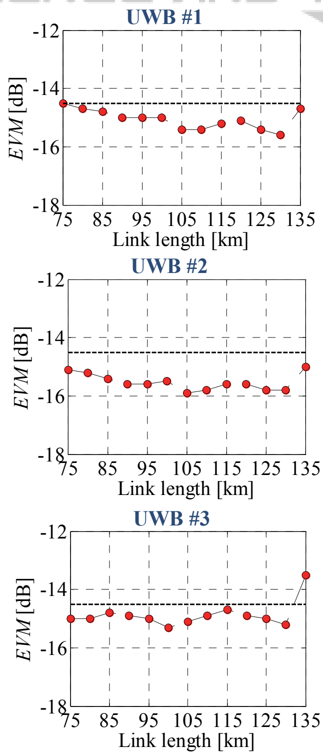


Figure 3: EVM of UWB band #1, #2 and #3 as a function of the LR-PON reach. The DCM is compensating for 2200 ps/nm and the modulation index is 13%.

In the following, the analysis of the EVM of the three UWB bands when the LR-PON reach varies between 75 km and 135 km is performed. This study is accomplished with a fixed dispersion compensation level in the DCM. From the results of Figures 2 (d), (e) and (f), the DCM is adjusted to compensate 2200 ps/nm of dispersion. In a 100 km-long LR-PON, this compensation level leads to a residual dispersion of -500 ps/nm. The modulation index of the multiplexed UWB signal applied to the DML is 13%. The fixed dispersion compensation level of the DCM and the modulation index value chosen correspond to the optimum system operating point shown in Figures 2 (d), (e) and (f).

Figure 3 shows the EVM of UWB band #1, #2 and #3 as a function of the LR-PON reach. LR-PON reaches between 75 km and 135 km are considered, which correspond to distribution fibre distances between 0 km and 60 km. Figure 3 shows that the EVM of the three UWB bands meets the EVM requirements of UWB standard (-14.5 dB) for LR-PON reaches between 75 km and 130 km. Moreover, Figure 3 shows also that, for almost all the LR-PON reaches analysed, UWB band #3 is the UWB band with worst performance. This is attributed to the limited frequency response of the electrical devices used in the experiments and also due to the reduced gain of the intensity response of the optical link observed for higher frequencies.

3.2 Multi-wavelength Operation

Our investigation of the single-channel LR-PON was also extended to a wavelength division multiplexing (WDM) LR-PON. This extension allows assessing the impact of the inter-channel crosstalk induced by adjacent optical channels on a WDM LR-PON. To perform this activity, two optical channels adjacent to the one used in the single-channel system were introduced into the system, as shown in Figure 1. However, these two additional optical channels were deployed using external modulation instead of direct modulation due to the lack of DMLs in our laboratory with adequate features to generate a dense WDM signal. Figure 4 shows the PSD of the WDM signal after the DCM inserted at the RN. Figure 4 shows that the spectra of the optical signal generated by the directly or externally modulated solutions are similar and, consequently, crosstalk features similar to the ones obtained if only directly modulated channels were employed are expected.

The two adjacent channels are generated through a distributed feedback laser (DFB) and an external cavity laser (ECL), and using 10 GHz Mach Zehnder modulators. The nominal wavelengths of the adjacent optical channels are set to 1552.65 nm and

1553.05 nm and, therefore, the channel spacing is 0.2 nm. The average optical power of the WDM signal launched into the feeder and distribution fibres is kept below 0 dBm to avoid degradation due to the nonlinear fibre transmission effects. The impact of the inter-channel linear crosstalk was performed for LR-PONs with reach of 75 km, 100 km and 130 km. As our focus is in directly modulated LR-PONs, we only evaluated the performance of the UWB bands transmitted in central optical channel.

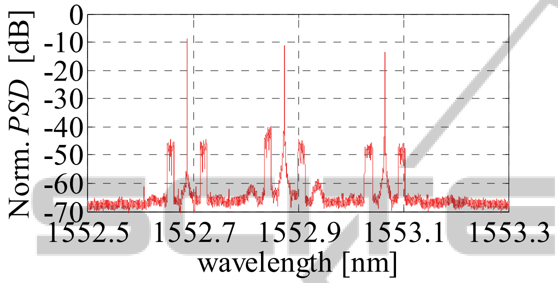


Figure 4: PSD of the WDM signal after the DCM inserted at the RN.

Table 1 presents the EVM results of the central channel of the WDM signal. Table 2 presents the EVM results of the UWB bands in single-channel operation, corresponding to the results of Figures 2(d), (e) and (f), as a reference. The comparison between the EVM results of Table 1 and Table 2 shows an EVM variation lower than 0.3 dB between single and WDM operation. This variation is mainly due to the fluctuation of the EVM measurements resulting from e. g. the noise introduced along the system. Those reduced EVM variations indicate that, for the channel spacing and the optical power levels considered in this work, the inter-channel linear and nonlinear crosstalks are not a relevant concern.

Table 1: EVM of the UWB signals transmitted by the central channel of a WDM signal comprising three optical channels.

EVM [dB]	UWB #1	UWB #2	UWB #3
75 km	-14.8	-15.0	-15.1
100 km	-15.1	-15.4	-15.3
130 km	-15.6	-15.6	-15.1

Table 2: EVM of the UWB signals transmitted in single-channel operation.

EVM [dB]	UWB #1	UWB #2	UWB #3
75 km	-14.5	-15.1	-15.0
100 km	-15.0	-15.5	-15.3
130 km	-15.6	-15.8	-15.2

4 CONCLUSIONS

The distribution of OFDM-UWB radio signals along LR-PONs employing directly modulated lasers has been demonstrated experimentally as an effective solution to serve users' premises located at 130 km away from the central office. Directly modulated LR-PONs has been also demonstrated as an effective solution to be deployed in sparse geographical areas, as EVM levels compliant with UWB standard are achieved for LR-PONs with reach between 75 km and 130 km, i. e., for a maximum distribution fibre reach of 55 km. In addition, the performance of the directly-modulated optical channel has shown an EVM variation lower than 0.3 dB when two adjacent channels (with a spacing of 0.2 nm) were introduced to assess the impact of the WDM operation.

This successful demonstration has been achieved by using fixed optical inline dispersion compensation at the RN and through adequate selection of the level of the UWB signal applied to the DML.

ACKNOWLEDGEMENTS

This work was supported by Fundação para a Ciência e a Tecnologia from Portugal under the TURBO-PTDC/EEA-TEL/104358/2008 project.

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