

Multi-Wavelength WiMAX-PONs with Overlapping Cells

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Abstract—An access network architecture integrating standard wireless signal formats over multi-wavelength splitter-PON based on radio over fiber (RoF) technology is demonstrated. Frequency division multiplexing (FDM) is applied to address individual base stations sharing a single wavelength. The extended wavelength band overlay overcomes the need for complex dispersion compensation techniques as it avoids the use of high frequency subcarriers in the FDM window. Also, it achieves enhanced network scalability to previously reported converged architectures as well as reduced component cost. Significantly, extended features of wireless networks have been presented through the application of overlapping cells to overcome the wireless spectrum congestion beyond current deployment scenarios and provide resilience for legacy PONs. To evaluate the network transmission characteristics, multiple IEEE802.16d channels, with 70 Mbits/s downstream and 40 Mbits/s upstream data rates, are frequency shifted around the same RF carrier and transmitted on two different wavelengths. The obtained results has demonstrated EVMs of -31 dB at ONU/BS remote antenna inputs and minimum 10^{-4} BERs bidirectionally over combined 20km and faded 330m overlapping micro-cells circumference without any error coding or relay techniques. The application of low-cost long-wavelength VCSEL array in upstream for colorless transmission demonstrated 0.7 dB power penalty to the received WiMAX channels in the OLT.

Index Terms— Radio-over-Fiber (RoF); Integrated PON-wireless access; wireless interoperability for microwave access (WiMAX);

I. INTRODUCTION

ALTHOUGH the escalating demand in bandwidth provision at close subscriber proximity could be widely met by optical technologies, next generation access networks should also provide great flexibility and mobility at ease of last-mile implementation [1]. To that extent convergence of optical and the rapidly growing by means of deployment and standards wireless networking, e.g. worldwide interoperability for microwave access (WiMAX) [2] and long

term evolution (LTE) [3], represents the challenge for the development of high capacity radio base-station backhauling links with centralized processing capabilities. In addition, to alleviate congestion, possible with currently deployed time division multiplexing passive optical networks (TDM-PONs), wavelength band overlay has been recently standardised and investigated to provide for higher network capacity and virtual point-to-point connectivity [4, 5].

In view of these requirements, an integrated network solution demonstrating transparent transmission of WiMAX signals over TDM-PONs has been investigated [6]. However, the applications of TDMA upstream, where all users are multiplexed on a single wavelength, unavoidable limits the wireless user bandwidth.

To that extent, this paper presents an innovative architectural platform demonstrating transparent transmission of FDM WiMAX channels in conjunction with extended wavelength band overlay over legacy PONs [4, 5]. This allows each optical network unit/base station (ONU/BS) allocated FDM subcarrier downstream to be dynamically multiplexed on different wavelengths relaxing the bandwidth requirements of optical and electrical components as well as providing for enhanced scalability by means of increased number of ONU/BSs. In addition, the use, in the devised network ONUs, of low-cost long-wavelength vertical cavity surface emitting laser (VCSEL) arrays [7] and tuneable optical band-pass filters (BPF) [4, 8] distinctively demonstrates colourless wireless-PONs with no requirement of wavelength-specific optical sources. Therefore, the distribution field remains intact in order to ensure smooth migration towards next generation PONs (NG-PONs) [5].

Another significant contribution of this paper is the network resilience demonstrated through multiple wavelengths drop via radio links, to users located in overlapping cells to potentially double their spectrum efficiency and provide alternative transmission path in case of fiber failure between a distribution point and an ONU/BS. The former extended feature of the wireless networks, compared to traditional WiMAX/LTE deployments, is justified through the significant reduction in base station cost by the application of the proposed RoF transmission. Alternatively, digital wireless backhauling solutions over traditional PONs could also be considered with the application of common public radio interface (CPRI) [9] techniques for simple base station implementation. However, this requires the continuous transmission of data between base

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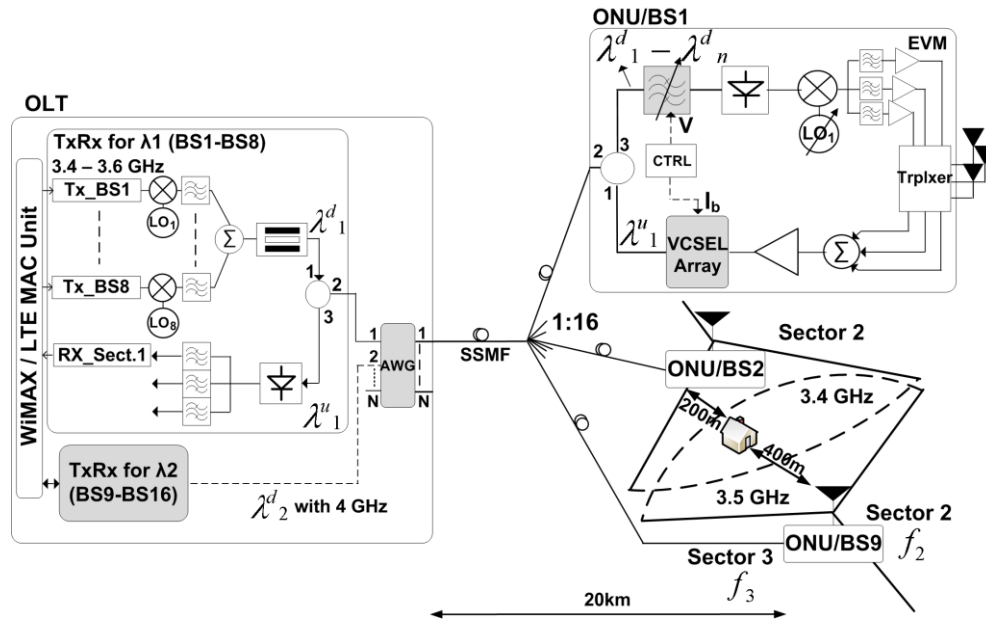


Fig. 1. WiMAX over multi-wavelength, splitter PONs.

stations and the central office in order to avoid limiting the wireless users' throughput. As a result, TDMA as used in traditional PONs would introduce unnecessary delays in the network upstream unless increased data rates are achieved over the optical network which unavoidably would lead to high component cost.

The rest of the paper is organized as follows. Section II describes the proposed network architecture outlining its key characteristics. This is followed by the detailed description of the modeling setup for optical and wireless signal formats. Section III involves the performance evaluation of standard WiMAX channels over optical and wireless links based on RoF and multi-wavelength overlay over splitter-based PON. Finally, Section IV offers some concluding remarks.

II. NETWORK OVERVIEW AND MODELING SETUP

A. Network Architecture Overview

A comprehensive diagram of the proposed network architecture, incorporating the developed modelling setup, is shown in Fig. 1. Any wavelength in the selected operating

spectrum could be partially or exclusively assigned to different ONU/BSs, providing in the latter service levels similar to wavelength division multiplexing PONs (WDM-PONs) without requiring any modifications in the remote node (RN). This is implemented by the addition of a dense array waveguide grating (AWG) in the optical line terminal (OLT) and tunable optical filters in ONU/BSs. For simplicity, the centre frequency of the latter can be adjusted from the OLT by means of a controller circuit. Unused AWG ports, shown in Fig. 1, could be exploited to assign a unique wavelength to each ONU/BS or to support multiple wireless-enabled PONs from a single OLT, considered as a prerequisite for NG-PONs [5]. This approach would also avoid interference with normal PON services since additional wavelength could be utilized, as recently defined by the IEEE802.3av standardization group [10].

On each wavelength, multiple microwave WiMAX channels are arranged in a FDM window to address individual ONU/BSs. The same FDM window could be carried on multiple wavelengths reducing maximum radio frequencies on an optical carrier. Consequently, high bandwidth optical and electrical components are not required. As detailed in Fig. 2, in downstream, the WiMAX licensed RF channels are shifted in frequency to address individual ONU/BSs using a predetermined LO and BPFs prior to being combined and modulated onto an optical carrier. An example of two frequencies at 4GHz and 5GHz are used in Fig. 2. At an ONU/BS a single LO, compared to multiple in a base-band approach [11], is only required operating on the same frequency, as in the OLT, for the specific ONU/BS to downshift the channels. Multiple BPFs are then needed to select each channel prior to transmission over the air.

A significant feature of the architecture compared to standard wireless network deployments is the centralised control that allows for the creation of overlapping

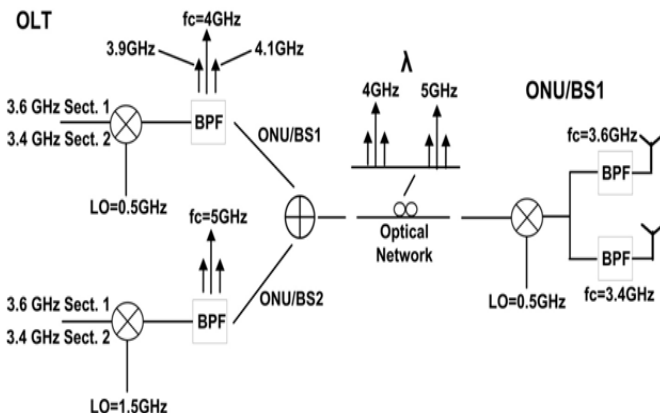


Fig. 2. The proposed FDM approach on a single wavelength.

cells/sectors, e.g. between ONU/BS2 and ONU/BS9 respectively in Fig. 1, operating at different frequency channels. Therefore, users that are in the overlapping regions can have simultaneous wireless support from multiple ONU/BSs, thus increasing the capacity of the wireless network and providing redundancy in case of fiber failure between a distribution node and an ONU due to established alternative routes for signal transmission. Since different ONU/BSs are operating on different radio channels no interference would be expected between overlapping wireless users and thus maintaining their network capacity. The transmission distances between ONU/BSs, shown in Fig. 1, allow for higher spectral efficiency compared to traditional WiMAX deployment while could be potentially extended with the application of relay techniques [12].

Another key characteristic of the proposed topology lays in the use of low-cost long-wavelength VCSEL arrays [7, 13] at ONU/BSs to demonstrate colorless terminations upstream with simple coupling optics. In contrast to RSOAs [14], VCSEL arrays do not require upstream wavelengths transmitted downstream. Although RSOAs could be possibly investigated [14], interference among multiple delayed versions of the upstream signal generated due to Rayleigh backscattering is known to potentially degrade performance. With VCSEL array approach re-modulation of downstream carriers is not required therefore avoiding the necessity of upstream wavelengths transmitted downstream simultaneously [14] with data for upstream modulation. The upstream wavelength selection can be managed by a means similar to tuning the ONU/BS filters.

The scalability of the architecture is currently being further investigated to demonstrate transmission of LTE [3] and other wideband emerging standards [15] exploiting overlapping cells concept. To that extent, it is easily extendable to such a topology since it provides signal transparency through the application of FDM.

B. Modeling Setup

A physical layer simulation test-bed was implemented using the industrial standard Virtual Photonics Inc. (VPI), enriched in functionalities in view of MATLAB programming, to build

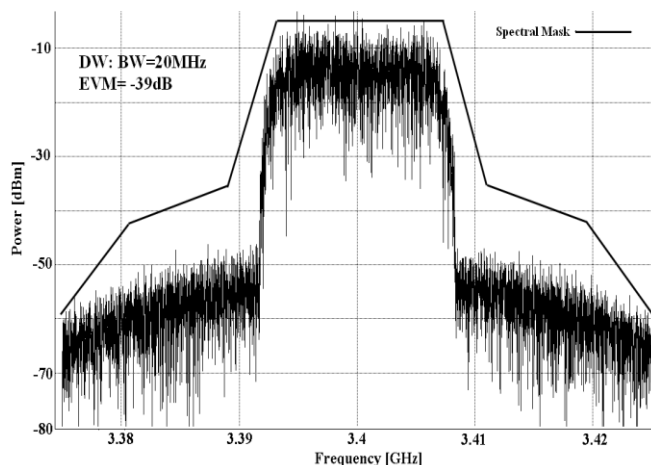


Fig. 3. WiMAX downstream transmitter spectrum at the OLT.

TABLE I
POWER BUDGET PARAMETERS FOR WiMAX AND GPON

IEEE802.16d WiMAX [16]			
Transmitters (DW/UP)		Receivers (DW/UP)	
Modulation	64- / 16-QAM	SS_antenna gain	17 dB
Channel BW	20 / 10 MHz	SS_cable loss	1 dB
EVM (dB)	-39 / -25 dB	Noise in BW ^a	-100.1/-104 dBm
Power at amplifier output	25 / 20 dBm	Noise Figure	4 dB
BS_antenna gain	17 dB	SS noise floor	-96.1 / -100 dBm
BS_cable loss	2 dB	SNR_required	24.4 / 18.2 dB
BS_antenna height	30 m	Rx sensitivity for BER=10 ⁻⁶	-71.7/ -81.8 dBm
EIRP	40 / 35 dBm	Shadow margin	8 dB
Propagation Loss with Cat. B [19]	100-120 dB		

ITU-T G984.2 GPON [15]					
OLT		RN Losses		ONU	
Laser Tx Power	+8.5dBm	SSMF	4 dB	Received Power DW	-17.8dBm
MZM Loss	3 dB	Splitter	14 dB	VCSEL Power UP	+1.2dBm
Circulator Loss	1 dB	Opt. BPF	3 dB		
AWG Loss	1.3 dB				
SSMF input power DW	=				
Received Power UP	+3.2dBm				
	-19.1dBm				

^aTypical thermal noise spectral density of -174 dBm/Hz is assumed at the receiver.

SS-Subscriber Station; EIRP-Effective Isotropic Radiated Power; DW/UP-Downstream/Upstream

an integrated simulation platform for the transmission of frequency shifted wireless channels over multi-wavelength GPON and overlapping cells. Performance evaluation measures include error vector magnitudes (EVMs) estimation at the remote antenna inputs for two base stations and the WiMAX received power at the radio receiver downstream and ONU/BS upstream with respect to bit error rate (BER) for various transmission distances of the proposed micro-cellular overlapping links.

Specified by the link-level model in Fig. 1, two Mach-Zehnder modulators (MZM), for Tx_BS1 and TxBS9, were used in the OLT to externally modulate a commercially available distributed feedback (DFB) laser sources with WiMAX channels applied at modulator's radio frequency (RF) input. The DFBs output powers were set to account for various optical component losses, specified in Table I for GPON [16], producing the maximum lunched power of +3.2 dBm into the fiber.

The three 70 Mbits/s downstream IEEE802.16d WiMAX channels for three sectors per base station are modeled in MATLAB [6]. They are then generated individually by Tx_BS1 and Tx_BS9, ranging from 3.4 to 3.6 GHz, with 100 MHz spacing. The spectral profile of WiMAX transmitters, given in Fig. 3, clearly satisfies the spectral mask specification of the standard to prevent excessive energy leakage outside the desired channel bandwidth [17]. Similar results for spectral mask were obtained for 10 MHz upstream transmitter.

Consequently, the WiMAX channel transmitted EVM, imposed by the non-linear high power amplifiers, is -39 dB, a figure higher than the minimum required by the standard for the 64-QAM modulation [17] as small RF powers are utilized to drive the MZM. It is important to mention here that, the reason this investigation was based on fixed WiMAX, rather than mobile counterpart [18], is because it is to be considered sufficient to demonstrate the concept of the proposed wireless/optical integration. The mobile WiMAX supports also OFDM modulation formats therefore from the physical layer prospective the same network performance is expected.

In addition, to include radio channel distance transmission limitations in the MATLAB models, not accounted for in the VPI simulation platform, practical wireless power budget parameters, as shown in Table I, were also considered resulting to the subscriber stations sensitivity of -71.1 dBm and -81.8 dBm downstream and upstream respectively [17].

As shown in Fig. 1, the WiMAX channels are then frequency shifted around the same 4 GHz RF subcarrier using a 500 MHz local oscillator. The same RF spectrum was utilized for both wavelengths to demonstrate the network scalability in terms of increased number of base stations as well as to provide for low-component costs due to the reduced total FDM bandwidth. Subsequently, signals from both transmitters are modulated on $\lambda_1^d=1553.33$ nm and $\lambda_2^d=1554.13$ nm and applied over the corresponding circulators, with 35dB port isolation and 1dB insertion loss, for bidirectional transmission. The modulated wavelengths are then multiplexed at the commercially available AWG and broadcasted to each ONU/BSs of the corresponding PON through 20km of standard single-mode fiber (SSMF).

At each ONU/BS, a tunable optical band-pass filter with 50 GHz bandwidth is used to select each wavelength which is then detected by an avalanche photodetector (APD) followed by RF subcarrier down-conversion to result to the transmitted WiMAX channels. To account for 1:16 splitter losses a 14 dB optical attenuator is used after the fiber. The resulting channels are then electrically filtered for each sector with 50 MHz BPF, amplified by non-linear high gain amplifier and transmitted over an AWGN and multi-path Stanford university interim (SUI-4) wireless channels [19]. Due to -70 dBm output power of the APD, cascaded amplification was considered with 55dB gain at each stage. In addition, the wireless channel model was designed in MATLAB to represent typical sub-urban environment for the fixed WiMAX operation. For the faded wireless path the cyclic prefix of 1/4 is included to reduce inters-symbol interference. The subscriber receiver is allocated in the overlapping region between two base stations as shown in Fig. 1.

Finally, in upstream, the two WiMAX channels at 3.4 GHz and 3.5 GHz from the overlapping sector are received by the ONU/BS2 and ONU/BS9 respectively and are directly modulated by a 6 mW biased VCSEL array at $\lambda_1^u=1553.33$ nm and $\lambda_2^u=1554.13$ nm to produce a constant output power level of +1.2 dBm [7] prior to being transmitted over 20km of

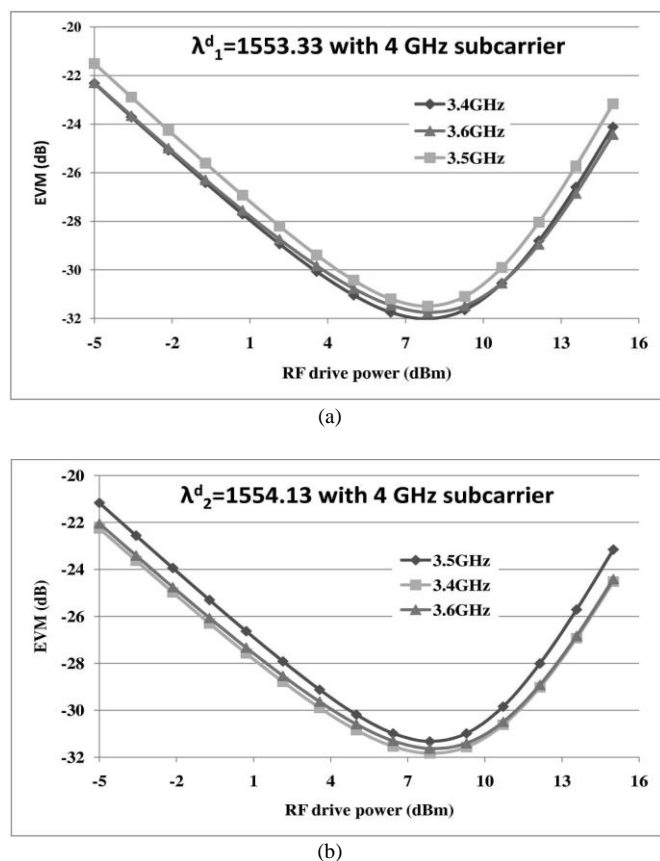


Fig. 4. EVM at remote antenna inputs for two wavelengths dropped to two ONU/BSs versus MZMs RF drive power.

SSMF. The upstream WiMAX channels comprise of a 16-QAM, 256-OFDM modulation with maximum data rate of 40 Mbits/s. The small-signal-gain amplifier in both ONU/BSs is utilized to drive the VCSEL laser array. Consequently, due to its grooming property, the same I/O port of the AWG as in downstream will be used before the signal is routed through the corresponding circulator to the destination receivers (Rx_Sect.X) in the OLT. The same circulator characteristics as in downstream were used for upstream transmission.

III. MODELING RESULTS AND TRANSMISSION EVALUATION

As nonlinear optical modulators could significantly degrade network performance, EVM characteristics as a function of the MZM RF drive power in the OLT were therefore initially estimated. The figures obtained were used to determine compliance with the WiMAX transmitter standard requirements at each remote ONU/BS antenna inputs for the two wavelengths. Therefore, after the wavelength selection and frequency downshifting by both base stations, an EVM figure of higher than -31 dB for certain RF drive powers is achieved, as shown in Fig. 4 (a) and (b), matching closely the WiMAX standard [17] with 64-QAM modulation. This demonstrates the network capability to transparently deliver WiMAX signals based on FDM to remote base stations over multi-wavelength-xPONs. As illustrated in Fig. 4, for both wavelengths, at low RF drive powers the signal is mainly distorted by noise while at high powers EVMs increase with MZM nonlinear affects as

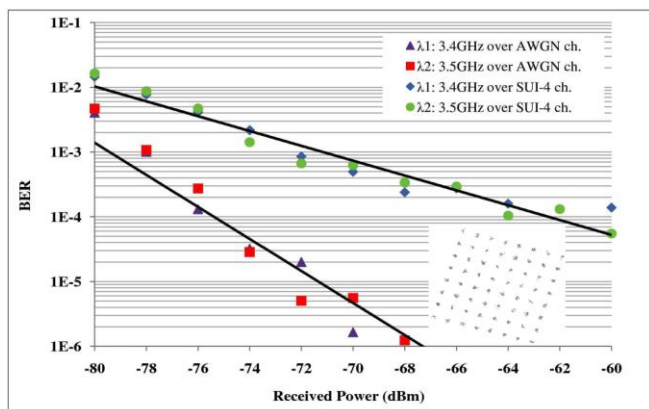


Fig. 5. BER versus received power for the WiMAX channels in the overlapping sector downstream.

expected.

Furthermore, to evaluate downstream transmission at a wireless receiver in the overlapping sector, as described by the link-level model in Fig. 1, two WiMAX channels, at 3.4 and 3.5 GHz, carried over the two wavelengths are transmitted to a single user with the power budget parameters specified in Table I. The BER curves were then plotted initially over a line-of-sight (LOS) AWGN, as specified by the standard [17], and faded non-line-of-sight (NLOS) wireless paths.

Consequently, for both WiMAX channels in the presence of an AWGN wireless path, the obtained results in Fig. 5 display power penalty of around 4 dB with respect to the 64-QAM downstream receiver sensitivity of -71.7 dBm for BER of 10^{-6} [17]. For a SUI-4 channel however, a further power penalty is monitored due to the multipath propagation. The observed power penalties for both wireless paths are expected to be improved with the application of forward error correction (FEC) techniques, as defined by the standard [17], which are excluded here to represent a worst case scenario. The BER characteristics of the other channels showed same performance since the model assume equal channel coefficients and power budget parameters for all sectors.

In addition, to predict the coverage across the overlapping sector, a modified empirically based path loss model, accepted by the IEEE802.16 working group for the fixed wireless

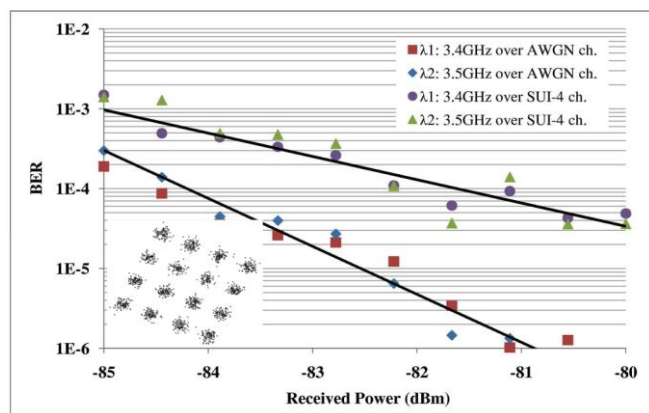


Fig. 6. BER versus received power for the WiMAX channels in the overlapping sector upstream.

transmission and expanded to cover higher frequencies [20], is then used based on power budget analysis parameters. To that extent, as shown in Fig. 5, for the BER of 10^{-6} the received power in the presence of the LOS AWGN un-coded channel is -67.7 dBm which with maximum transmission power of $+40$ dBm corresponds to the attenuation value of 107.7 dB. For the category B channel and base station antenna height of 30 m [20], the maximum achievable transmission distance is thus 430 m which is comparable with some practical deployment scenarios [21]. This is expected to be extended however with the application of FEC. The channel estimation algorithms at the wireless receiver and synchronization issues were not considered as these are vendor specific and are therefore out of the scope of this paper. Significantly, BERs of 10^{-4} were achieved for wireless channels, with the received power of -63 dBm, confirming error-free transmission with the maximum coverage of around 330 m for certain services [22].

In upstream, the BER for the two WiMAX channels in the overlapping sector versus received power at the ONU/BSs is evaluated in the OLT wireless receiver. As shown in Fig. 6, for an AWGN channel, the power penalty is about 0.7 dB which is lower than in downstream. For the SUI-4 channel further power penalty is observed similar to downstream. However, the BER of 10^{-4} could also be achieved for both channels with distinctive received powers. The obtained results upstream confirms that signal distortion due to the interaction of laser chirp and fiber dispersion in long-wavelength direct VCSEL array modulation is not significant in the proposed WiMAX-PON network.

Finally, the received constellation diagrams obtained at the wireless receivers prior to gain and phase compensation, displayed as insets in Fig. 5 and 6, show the rotation due to the optical filter phase response and direct laser modulation respectively. In both directions the received constellations are obtained at BER of 10^{-4} . The pilot tones for the channel coefficients estimation, as described by the standard [17], were not used since perfect channel knowledge is assumed at the receiver. The constellation diagrams are used for the estimation of the EVM.

IV. CONCLUSION

A highly-scalable network topology is described featuring transparent wireless transmission by means of FDM over multi-wavelength legacy PONs, requiring the slightest modifications in hardware through the use of single AWG and low-cost long-wavelength VCSEL arrays in the OLT and ONU/BSs respectively. Significantly, extended wavelength band overlay provides for low frequency windows and consequently no dispersion compensation. In addition, it allows for small bandwidth optical and electrical devices. Also, an enhanced network dynamicity and resilience through overlapping cells is presented by routing multiple-wavelengths to a single user via a radio link. The optical network transparency to WiMAX channels has been demonstrated through obtained EVM figures of -31 dB for 64-QAM

WiMAX downstream channels, measured at ONU/BSs antenna inputs as required by the standard. In addition, 4 dB power penalty downstream and 0.7 dB upstream was monitored for 70 Mbps/s and 40 Mbps/s channels respectively transmitted over combined multi-wavelength 20km PONs and 430m AWGN wireless path in the absence of channel error coding and relay techniques. Furthermore, minimum BERs of 10^{-4} for the two channels bidirectionally were obtained over SUI-4 330m overlapping cell circumferences. Finally, the ability of the architecture to support multiple radio-PONs on a single AWG offers a cost-effective solution for service delivery to a large number of remote users, since its deployment is of significantly lower cost in relation to traditional wireless solutions.

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