Interoperability of GPON and WiMAX for Network Capacity Enhancement and Resilience

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The interoperability of standard WiMAX and GPON is shown to overcome the wireless spectrum congestion and provide resilience for GPON through the use of overlapping radio cells. The application of centralised control in the optical line terminal (OLT) and time division multiplexing for upstream transmission enables efficient dynamic bandwidth allocation for wireless users on a single wavelength as well as minimised optical beat interference at the optical receiver. The viability of bidirectional transmission of multiple un-coded IEEE802.16d channels by means of a single radio frequency (RF) subcarrier at transmission rates of 50 Mbits/s and 15 Mbits/s downstream and upstream respectively for distances of up to 21 km of integrated GPON and WiMAX micro-cell links is demonstrated.

OCIS codes: 060.4250, 060.4510.

Introduction

The emergence of new bandwidth-intensive applications articulated by distance learning, online gaming and movie delivery by means of high-definition video are providing the impetus for upgrading the access network infrastructure to establish broadband pipes at close proximity to the user. Passive optical networks (PONs) offer more opportunities to communicate these services than ever before, providing for the necessary connection speeds per user of 100 Mbits/s [1]. Although PONs can provide high-bandwidth and quality of service (QoS), the deployment cost in particular of running fibre from street cabinets to the home is currently relatively high [2]. Beyond that, in a typical tree topology, such as the Gigabit-PON (GPON) [3], redundancy is required in case of fibre failure between a distribution node and an optical network unit (ONU). The various possible methods on providing redundancy are summarised in [4], however, all suggest that dual-fibre should be used that leads to high investment costs for operators. By contrast, wireless access networks require less infrastructure deployment and can provide ubiquitous access connections to end users. In addition, broadband wireless technologies, such as WiMAX [5], are gradually developing to expand their bandwidth capacity, coverage and QoS, to complement their established mobility. Hence, a viable access solution for the future could be obtained by leveraging the advantages of both technologies combined on an integrated architectural platform [6]. In order to minimise network installation and maintenance costs, it would be desirable to make radio antenna units as simple as possible by shifting expensive devices and signal processing at the centralised head-end through the use of radio-over-fibre (RoF). Additionally, to the clear cost saving in hardware, such infrastructure would benefit from a flat control plane and seamless convergence by which signalling and control messages are directly exchanged between the optical line terminal (OLT) and end users [7, 8].

An original radio-over-fibre access network architecture is described and investigated to provide WiMAX functionality features over deployed GPON platforms, primarily aiming to enable redundancy in GPON through wireless connections as well as to improve wireless spectrum congestion and thus increase the WiMAX network capacity. This has been achieved by introducing, for the first time, the concept of overlapping radio cells centrally controlled by the OLT. In comparison, published work in converged optical-wireless networks with respect to network connectivity and fault-tolerance [7] is based on interconnected wireless routers distributed in the locality of ONU base station gateways. Since the wireless routers are configured on a mesh topology user data would need to travel over multiple hops in the field on route to corresponding ONUs imposing extensive resource allocation and complicated routing algorithms to achieve resilience [9]. In contrast, each ONU in the proposed architecture simply serves as a wireless signal relay, providing direct connectivity to wireless users in agreement with typical cell deployment. On-demand bandwidth provisioning to further enhance WiMAX capacity is demonstrated by dynamically dropping additional WiMAX channels to congested ONU/base stations (BSs), centrally by the OLT. In addition, resilience is achieved due to the overlapping cells since channels from neighbouring ONU/BSs could be used to access users in the coverage area of a failing base station.

Another feature of the architecture is the ability to form WiMAX micro-cells to cover larger geographical areas, compared to pico-cells [8], which can potentially increase the reach of standard GPONs. To effectively exploit the transmission capacity of the fibre medium in the downstream, multiple microwave WiMAX channels are transmitted over the GPON on a single optical carrier utilising subcarrier multiplexing (SCM) [10] for each ONU/BS, reducing network cost. Significantly, to avoid the optical beat interference at the photoreceiver upstream, a single optical carrier in the proposed architecture is shared by multiple ONU/BSs by using time division multiplexing (TDM), as opposed to a multi-wavelength approach [11] that can result in high capital and operational costs [12].

Network architecture

The proposed network architecture, depicted in Fig. 1, consists of a standard GPON with novel wireless-enabled OLT and ONUs. At the OLT after WiMAX symbols are generated by multiple transmitters they are upconverted to a subcarrier for each wireless-enabled ONU. The subcarrier multiplexing technique was used to ensure signal transparency for various radio signal formats and to avoid interference with the GPON spectrum. Each WiMAX transmitter at the OLT is serving a single radio cell at an ONU/BS that is divided into small parts called sectors in order to make the cell more efficient in terms of reduced co-channel interference and increased capacity. The ONU/BSs are therefore responsible only for downconversion of received downstream channels and for GPON processing.

The key feature of the proposed architecture is the deployment of small radio cells with high spectral efficiency, enabled through the reduced ONU/BS cost based on central processing and control from the OLT. The centralised control, compared to the distributed approach in a traditional WiMAX deployment allows for the creation of overlapping cells, e.g. between Sector 2 and Sector 1 of ONU/BS2 and

ONU/BS1 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 WiMAX network and providing redundancy in case of fibre 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. Additionally, in case of fibre failure between a distribution node and an ONU only a single wireless channel could be available in an overlapping region. This might result in lower data rate availability per user since the remaining channel penetration is increased. This has been accounted for in the proposed architecture by the capability of utilising additional wireless channels to failing ONU/BSs.

Another significant characteristic of the architecture offered by the centralised control from the OLT and the application of SCM is efficient multiple channel allocation per wireless sectors, accommodating on-demand bandwidth allocation across a sector, in contrast with traditional WiMAX deployments where the base stations are deployed independently and dynamic bandwidth allocation is not possible.

To allow simultaneous WiMAX and GPON transmissions and thus achieve a fixed-to-mobile convergence (FMC) platform, the wireless channels were transmitted through the optical fibre by means of SCM. A different RF subcarrier was dedicated to each ONU/BS in downstream to enable concurrent transmission of multiple WiMAX channels to serve each ONU antenna. Within the OLT, standard microwave orthogonal frequency division multiplexing (OFDM) WiMAX symbols [5], generated by Transmitter (Tx) for BS_n, for different sectors in each ONU/BS were up-converted to the predetermined RF subcarriers spectrum before they were combined with the packets for wired users and subsequently modulated onto the optical carrier for 20 km fibre downstream transmission. To ensure minimum interference with the GPON baseband spectrum, individual RF subcarriers centred at 4 GHz and above, are utilised as indicated in Fig. 1. A 1 GHz spacing between the centre RF subcarriers was considered in order to reduce electrical filter design complexity in the OLT and consequently minimise the possible subcarrier interference due to inter-modulation products created by an optical modulator [10].

Significantly, in case the total bandwidth demand across a wireless cell cannot be met by an ONU/BS, an additional channel for a sector, e.g. 3.9 GHz for Sector 1 of Tx for BS1, on a single wavelength downstream can then be provided. A 500 MHz wide bandpass filter (BPF) was designed to accommodate the transmission of all required channels. The total number of different WiMAX channels needed from the OLT was determined by a frequency reuse plan for a designed deployment scenario. Three radio sectors per antenna each operating at different frequencies, 1:3:3 reuse factor, requiring a minimum of three WiMAX channels per ONU/BS antenna plus additional channels for on-demand bandwidth provisioning are illustrated in Fig. 1. After the up-converted WiMAX channels were combined with the GPON user data [13], they were then broadcast to all ONU/BSs on the same optical carrier in downstream. In practical deployment scenarios these WiMAX channels could be leased to single or multiple operators by means of dedicated ONU/BSs.

At an ONU/BS, as shown in Fig. 1, the combined signals were first demultiplexed into two elements: a baseband GPON signal and the up-converted WiMAX channels. The baseband signal is then forwarded to the GPON downlink (DW) port for further processing and the microwave channels were down-converted by a mixer using the same local oscillator (LO) frequency as in the OLT. The BPFs then select the required WiMAX channel prior to signal transmission for wireless users across a sector with 1 km proximity. In order to support additional channel drop to a sector, tuneable BPFs must be used. Based on information in the OLT downstream frame, the centre frequency of the filters can be controlled by a system-on-chip platform already available in a GPON processing module. In addition, to reduce the count of BPFs required in an ONU/BS, a single filter can be potentially shared by multiple WiMAX channels by assigning different transmission time-slots for each filter managed from the GPON processor.

An additional feature of the architecture lies in upstream transmission where wired and wireless users share a single optical carrier in time domain resulting in optical signals from all ONU/BSs arriving at different times at the OLT. The overall network upstream transmission would be governed by TDMA to conform to the GPON standard, defining each ONU transmission window to approximately 150 μs [14]. These transmission window slots would be used by the WiMAX medium access (MAC) unit in the OLT to schedule the transmitting upstream wireless channels, interleaved inside each WiMAX uplink map. Due to the synchronization of the former with the latter no buffering would be introduced in the ONU or OLT. In addition, since encapsulation of WiMAX packets into GPON frames is avoided no modifications in the WiMAX frame format would be required. Therefore, the overall network delay and throughput performance will conform to the GPON delay and throughput figures and will depend on the TDMA-PON upstream polling cycles [15, 16]. Based on this approach the optical beat interference at the OLT receiver is minimised as well as a single photoreceiver and WiMAX demodulator is only needed reducing the overall design complexity of the OLT. Also, another important characteristic enabled by the use of time division multiplexing is that the upconversion to a RF subcarrier is not required, decreasing the BPFs and mixer count at an ONU/BS as well as avoiding generation of additional intermodulation products at high frequencies due to laser chirp [17]. Wireless users from all sectors communicate directly to registered ONU/BSs via a microwave link that performs amplification of the received radio channels and transmit it together with GPON packets in assigned time-slots back to the OLT. The interference with GPON spectrum is avoided since the WiMAX radio channels occupy the spectrum above 2.5 GHz.

The maximum bandwidth distributed by an ONU/BS is determined by frequency regulation issues specified for a particular deployment scenario. However, as proposed wireless base stations are controlled centrally, small densely spaced cells can be provided supporting wide channel bandwidth with a maximum of 70 Mbits/s aggregate data capacity per channel downstream which is compatible with the WiMAX standard [5]. For higher data rate service provisioning including high definition TV (HDTV) and video-on-demand (VoD), additional channels can be delivered efficiently to a sector to increase the cell capacity. It is anticipated that up to 50 users per ONU/BS radio sector can be supported, which is consistent with the recent research trend for future network capacity demand [18]. Finally, to further improve the spectrum efficiency and the maximum bandwidth supported across radio cells, smart antennas such as Multiple-Input-Multiple-Output (MIMO) [19] or adaptive beam-forming technique [20] could also be used at the ONU/BSs.

Network modeling and simulation results

In order to demonstrate the capability of the new architecture to transmit IEEE802.16d WiMAX channels successfully over combined GPON and radio-cell links a physical layer simulation test-bed was implemented using Virtual Photonic Inc. (VPI) and MATLAB as shown in Fig. 2.

In the downstream the performance of five WiMAX channels was modelled with no channel coding applied in order to present a worst case scenario. The WiMAX OFDM transmitter was modelled in MATLAB and VPI in order to emulate a 10 MHz wide 64-QAM OFDM channel with 256-point Inverse Fast Fourier Transform (IFFT), 64 samples cyclic prefix and 55 guard subcarriers corresponding to maximum attainable data rate across a cell of 50 Mbits/s [5]. The WiMAX transmitter and receiver block diagrams are shown in Fig. 3 that clearly demonstrates the interworking functionalities of the relevant modelling platforms with reference to the integration of GPONs and WiMAX. At the transmitter, following symbol formation the subcarrier mapping block inserts guard carriers and a cyclic prefix to combat the effect of wireless channel multipath propagation. The resulting frequency domain signal, before being transmitted over GPON, was subsequently transformed to the time domain using the IFFT prior to a digital-to-analog conversion (D/A) and signal shaping. At the other end, the WiMAX receiver, detected the received symbols by performing the inverse functions of the transmitter and hence determined the bit error rate (BER). The 11 bits D/A and A/D converters at the transmitter and receiver respectively were used in order to minimise quantisation noise.

Five downstream WiMAX channels from 3.3-3.7 GHz at the OLT, with 100 MHz spacing, were up-converted using a 500 MHz LO before being applied to a Gaussian BPF with a 4 GHz centre frequency and 500 MHz bandwidth. The bandwidth of the filter allows for five 100 MHz spaced WiMAX channels to be transmitted simultaneously to a single ONU/BS. Furthermore, an additional subcarrier at 5 GHz was added to simulate potential crosstalk between the two neighbouring subcarriers.

A Mach-Zehnder modulator (MZM) was used in the OLT for downstream to externally modulate a distributed feedback laser (DFB) providing constant output power of +5 dBm at 1490 nm [21], to account for the MZM's typical loss of 5 dB alongside additional losses occurred throughout the transmission link and network elements. After transmission over the 20 km SSMF the optical signal was detected by an avalanche photo-detector (APD) in the ONU/BS. A fixed attenuator before the APD receiver was used to model the loss of a 1:64 splitter.

To observe the worst case scenario in the presence of intermodulation products, a maximum RF drive-power of +20 dBm was considered into the RF input of the MZM. The detected WiMAX channels at the APD output are shown as the inset in Fig. 2. It should be noted that the MZM produced second order intermodulation products that could potentially limit the transmission bandwidth and degrade the BER performance. It has been suggested that octave wide RF subcarriers will cause intermodulation products to appear outside the desired bandwidth of transmission, particularly in direct laser modulation where a laser is driven in the linear region of its transfer function curve only to avoid the modulation clipping [10]. This would, however, limit the maximum number of allowed RF subcarriers. An external modulator, on the other hand, can operate in the nonlinear region and therefore be able to control the unwanted intermodulation products. Consequently, the RF subcarriers from the OLT can occupy wider bandwidth in comparison with direct modulation. Finally, fibre non-linear effects, such as self-phase modulation (SPM) and cross-phase modulation (XPM), do not limit the network performance due to the low power levels launched into the fibre as well as for the short transmission distances used [10].

Measurements from the received WiMAX channels, after the down-conversion and BPF in the ONU/BS, indicated that the adjacent channel leakage ratio (ACLR) at an offset frequency of 20 MHz was 40 dB. It should be noted that the ACLR is an important parameter in wireless communication in order to avoid the performance degradation in neighbouring frequency bands and it is mainly determined by thermal and shot-noise at the optical receiver and the bandwidth of the shaping filter that is used in the WiMAX transmitter [22].

The error vector magnitudes (EVMs) for the five WiMAX channels, as a function of the RF drive power into the MZM, were plotted to indicate if the maximum allowable RF drive power into the MZM comply with the WiMAX transmitter requirements. To that extend the RF drive power for each channel was varied from -5 dBm to +20 dBm while keeping the received optical power at the APD fixed. The average simulated EVM values of all channels, where for low input power levels into the MZM the performance is limited by thermal and shot noise of the photo-detector, while for high power levels, nonlinear distortions of the MZM increase EVMs, are shown in Fig. 4. For the 64-QAM WiMAX OFDM transmitter an EVM of -31 dB was obtained, matching closely the performance figure of the WiMAX standard [5] to ensure acceptable performance for wireless users in terms of bit error rate. According to Fig. 4 EVMs of -31 dB were recorded at the ONU/BS antenna for all wireless channels with RF drive powers between +7.5 dBm and +9 dBm. For lower modulation levels, e.g. 16-QAM, higher EVM values can be tolerated allowing for greater RF drive power levels into the MZM thus minimising intermodulation products at the photoreceiver.

Before transmission of the signal over a wireless channel, following the down-conversion in the ONU/BS, the system must provide sufficient received power to ensure that the minimum signal-to-noise ratio (SNR) is met at all times. Since the power level of the detected subcarriers after the APD is low, high gain power amplifiers are required prior to transmission over the wireless channel. A modified empirically based path loss model, accepted by the IEEE802.16 working group and expanded to cover higher frequencies [23], can then be used to predict coverage of the wireless network based on power budget analysis parameters. With typical parameters of WiMAX compliant equipment, 1 km coverage for each sector is expected. Furthermore, in order to consider multipath propagation the standard Stanford University Interim (SUI)-4 channel profile with a moderate delay spread, shown in Table 1 and modelled in MATLAB with a single-input-single-output antenna configuration, was utilised since it provided a satisfactory representation of the urban and suburban macro-cellular environments [24]. The maximum of three paths were included where K of zero for each path demonstrates non-line-of-sight wireless link between the transmitter and the receiver. Also the channel imposes maximum delay and attenuation of 4 μs and 8 dB respectively on the received signal. Finally, the switches after the amplifiers, which are shown in Fig. 2, act as multiplexers or de-multiplexers to enable bidirectional wireless transmission.

Five un-coded WiMAX carriers were therefore transmitted across the SUI-4 channel assuming perfect channel knowledge at the receiver. To perform BER evaluations on the received wireless signals a combination of Gaussian and exponential distributions was used since the WiMAX carriers are affected by additive white Gaussian noise and multipath propagation as well as by non-linear effects on the optical link [25]. Bit error rate plots for all five WiMAX channels each employing 50 Mbits/s data transmission with 64-QAM OFDM modulation, are shown in Fig. 5. Based on field trial measurements to support services such as IPTV [26], online gaming and video streaming and specified by the international telecom union (ITU) recommendation and 3GPP technical specifications [27, 28], BERs of 1E-4 are considered acceptable for error free transmission. The proposed architecture has displayed BER figures of 1E-4 at an SNR requirement of 24 dB for all carriers obtained by varying the signal-to-noise ratio of the wireless channel with -30 dBm fixed received power at the APD [21]. The application of wireless channel coding techniques, such as convolution or turbo codes, is expected to reduce the recorded worst-case SNRs to less than 22 dB, specified in the WiMAX standard for downstream transmission [5]. Significantly the demonstrated 50 Mbit/s aggregate downstream capacity per WiMAX channel has been achieved at aggregate transmission links extended to 21 km as opposed to a limited 1 km with standard WiMAX deployment. Alternatively each subscriber could benefit from higher bandwidth achieved in the presence of smaller concentration of wireless users per radio cell, enabled due to the lower cost per base station and as a result smaller cell size. Furthermore, in case the bandwidth requirement of users in a cell or sector exceeds the aggregate capacity, additional wireless channels at 3.6 GHz and 3.7 GHz could be successfully deployed from the OLT, as shown in Fig. 5, to enable on-demand bandwidth provisioning. GPON redundancy in case of a fibre failure could also be supported by instead of using the additional carriers to increase capacity of individual users in a cell, to employ them as alternative connections to another ONU/BS in its vicinity.

Finally the constellation diagram, shown as an inset in Fig.5, represents the obtained 64-QAM data points at the 3.5 GHz WiMAX receiver employed also to define the EVM of Fig. 4.

In upstream, the same five WiMAX channels were utilised to assess the BER performance at the OLT after transmission over the SUI-4 and GPON links. Each upstream WiMAX channel comprises 16-QAM, 256-OFDM occupying 5 MHz bandwidth with the same number of guard carriers and cyclic prefix size as in downstream, corresponding to maximum attainable data rates of 15 Mbits/s [5]. Subsequent to signal reception at the ONU/BS, direct laser modulation with a constant output power level of +5 dBm prior to transmission over a 20 km SSMF was utilised to comply with current GPON deployment [21]. At the OLT, after the circulator, the received signal was converted to the electrical domain by an APD before symbol detection in a WiMAX receiver. In order to determine the operating range of the direct modulated laser for optimum performance, in a similar manner to downstream, the optical modulation index (OMI) against EVM at the OLT was measured and displayed in Fig. 6 for upstream channels transmitted over the GPON only. The minimum EVM of -24 dB was obtained for the wireless channel at 3.3 GHz channel. Intermodulation products, created by the interaction between laser chirp and fibre dispersion have affected channel performance to variable extends. This was also confirmed by the BER responses of the five WiMAX channels used in upstream where a power penalty of 3 dB was measured at a BER of $1E^{-4}$ between the 3.3 GHz and 3.7 GHz channels. As already stated the SNR is expected to improve with appropriate wireless channel coding or with lower dispersion fibre and reduced laser chirp. The obtained 16-QAM constellation diagram, shown as an inset in Fig.7, demonstrates the constellation rotation due to the direct laser modulation.

Further SNR improvements can be expected with transmission diversity with multiple antenna elements at the ONU/BS and/or subscriber stations. Finally, wireless devices can exploit the benefits of cognitive radio technology as well by utilising dynamic spectrum access across radio cells and consequently increase the network capacity [29].

Conclusions

The innovative broadband access network architecture described in this paper exploits the merits of standard GPON and WiMAX technologies to capture the best attributes of each, seeking to facilitate high QoS provisioning in wire-line networks and ubiquitous connection together with the low deployment cost and mobility of wireless networks. The maximum EVMs of -30 dB in downstream and -24 dB in upstream for all channels were obtained as required by typical WiMAX transceivers. BER transmission characteristics against SNR from the physical layer simulation test-bed showed $1E^{-4}$ error rate for 50 Mbits/s and 15 Mbits/s data capacity per channel in downstream and upstream respectively over GPON and wireless cells. The SNR values are expected to improve with wireless channel coding in order to comply with the WiMAX standard transceivers. The obtained data rates and error free transmission demonstrate the capability of the architecture to deliver services such as IPTV, online gaming and video streaming not feasible with the current WiMAX deployment. Further analysis showed dynamic resource allocation per ONU/BS cell providing an additional channel for wireless transmission and thus improved capacity for even higher bandwidth services. In downstream, the WiMAX channels were transmitted on RF subcarriers for each ONU/BS in order to avoid the interference with the baseband GPON transmission and to use optical fibre efficiently. The time sharing of the optical carrier between wireless and wired signals in upstream minimises the optical beat interference at the OLT photoreceiver without the need for additional wavelengths and RF upconversion at an ONU/BS. Significantly, the proposed centrally controlled ONU/BSs, in comparison with distributed control in a typical WiMAX deployment, allowed for creation of the overlapping cells which enabled for improved GPON redundancy in case of fibre failure between a distribution point and an ONU as well as enhanced WiMAX capacity.

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LIST OF FIGURES

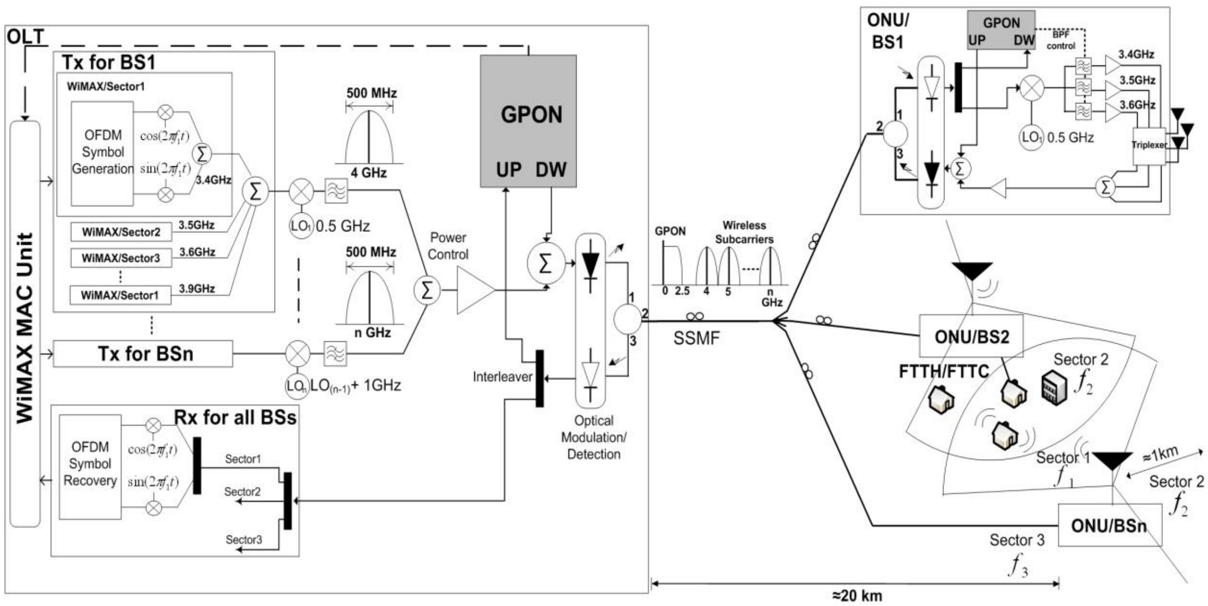

Fig. 1. WiMAX over GPON architectural platform

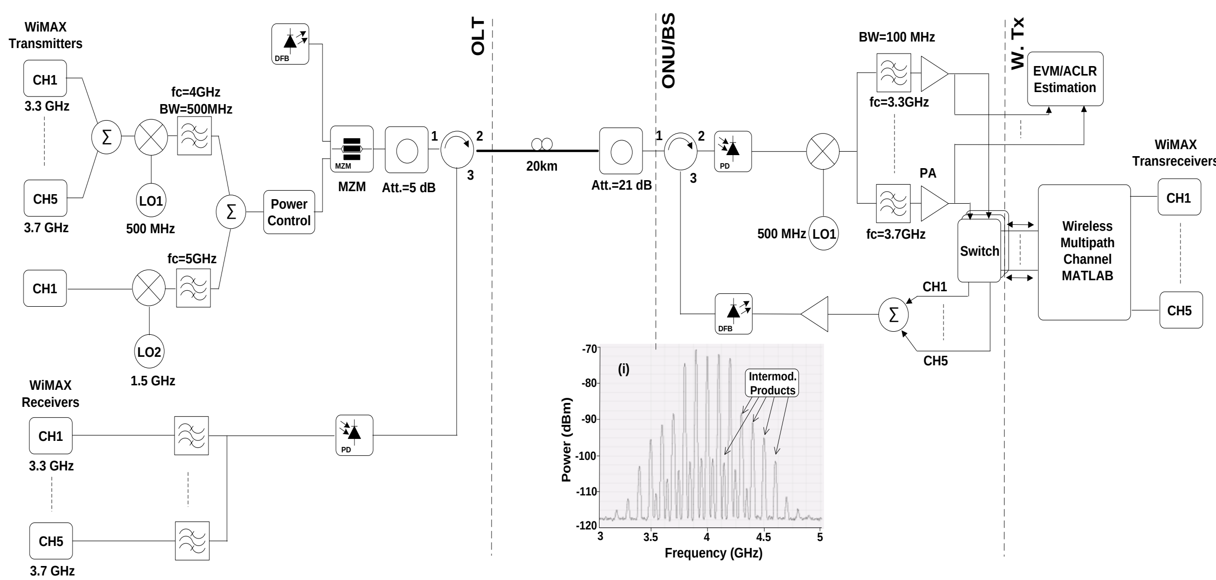

Fig. 2. WiMAX over GPON physical layer simulation test-bed

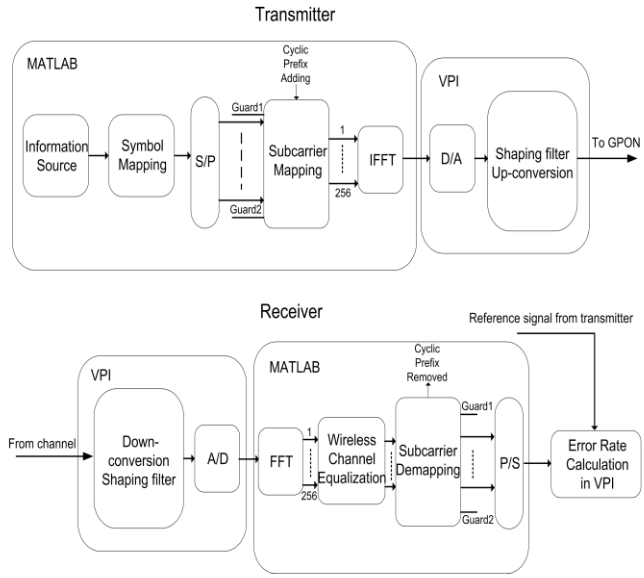

Fig. 3. WiMAX transmitter and receiver models

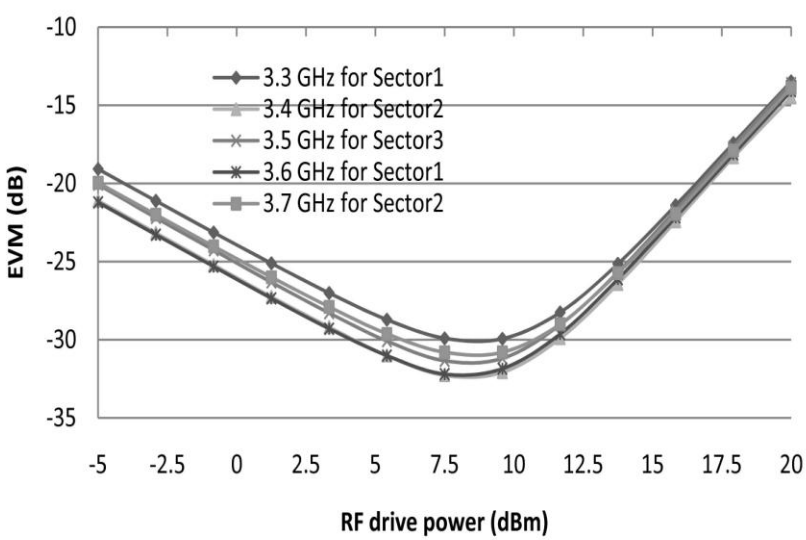

Fig. 4. EVM versus RF drive power for downstream WiMAX channels

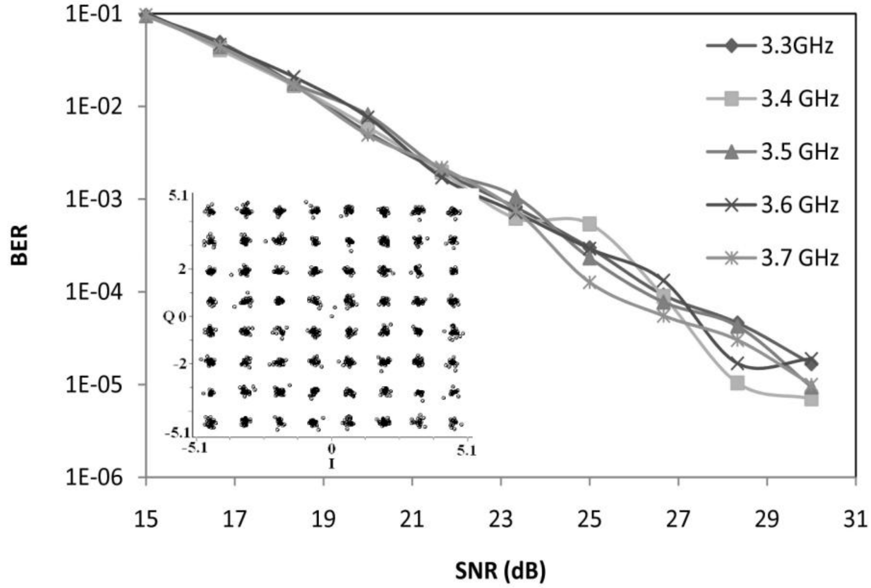

Fig. 5. BER versus SNR for 50 Mbits/s 64-QAM OFDM channels over GPON and SUI-4

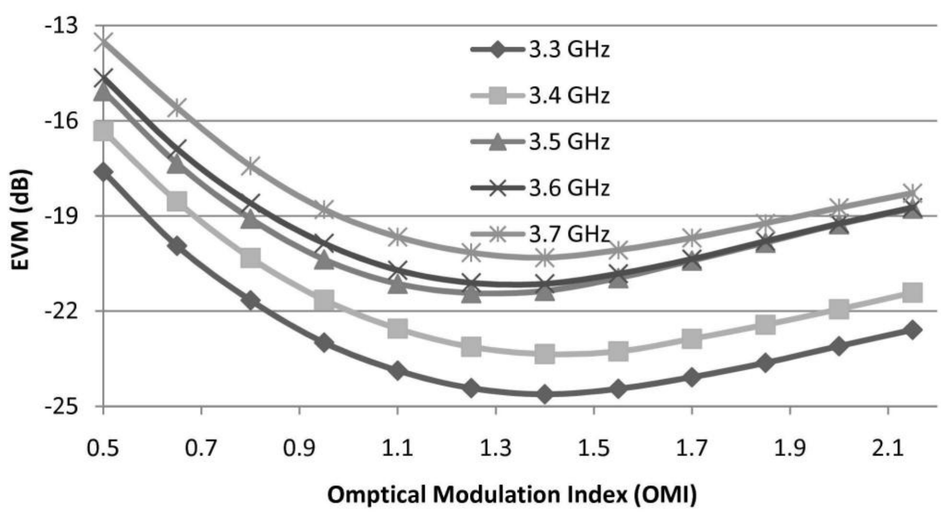

Fig. 6. EVM versus OMI for upstream WiMAX channels

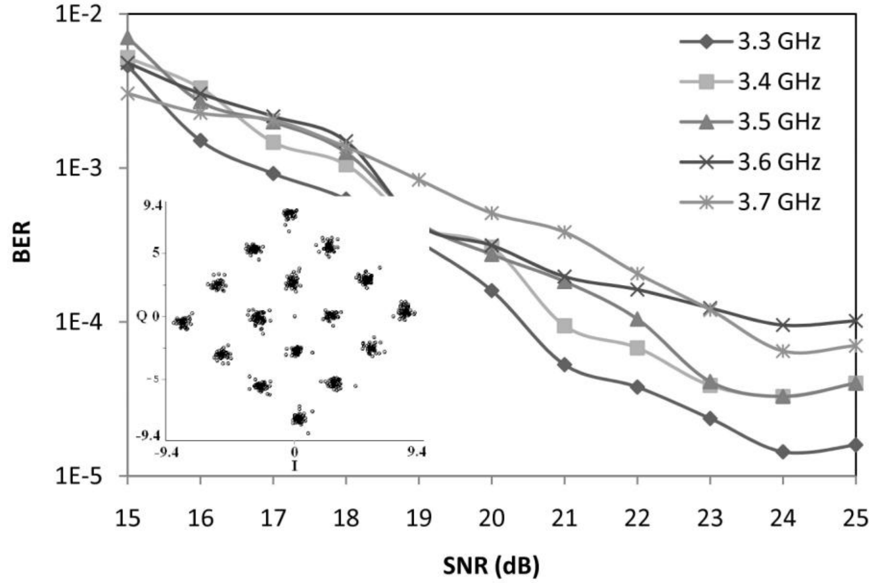

Fig. 7. BER versus SNR for 15 Mbits/s 16-QAM OFDM channels over SUI-4 and GPON

TABLES

Table 1. Standardized SUI-4 channel for IEEE 802.16d

SUI-4 Channel Model			
	Tap 1	Tap 2	Tap 3
Delay (μs)	0	1.5	4
Power (dB)	0	-4	-8
K factor	0	0	0