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Dynamic wired-wireless architecture for WDM stacking access networks

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Abstract
This paper presents a dynamic architecture for convergent wired and wireless access networks in Time Division Multiplexing (TDM) based Passive Optical Network (PON) featuring wavelength stacking. Four wavelengths for wired services carrying 10 Gb/s traffic load, one shared extra reconfigurable wavelength and one wavelength common to all Optical Network Units (ONUs) for the transport of wireless services were launched into a 1:64 splitting ratio PON network. In the ONU, a tunable free spaced Fourier optics based filter selects one of the wavelengths conveying wired services and a tunable Fiber Bragg Grating (FBG) filters out the wavelength carrying the wireless services. In the uplink direction, subcarrier multiplexing (SCM) was used for the combined transport of the wired and wireless signals to the Central Office (CO).

Keywords: Access Networks, Dynamic Wavelength Allocation, Optical Filters, WDM Stacking, Wired-Wireless Convergence.

Arquitectura dinámica fija-móvil para redes de acceso WDM apiladas

Resumen
Este artículo presenta una arquitectura dinámica para redes de acceso convergentes fijas e inalámbricas en red óptica pasiva (PON) basada en multiplexación en división de tiempo (TDM) bajo el paradigma de apilamiento de longitudes de onda. Cuatro longitudes de onda para servicios fijos transportando una carga de tráfico de 10 Gb/s, una longitud de onda reconfigurable extra y una longitud de onda común a todas las unidades de red óptica (ONU) para el transporte de servicios inalámbricos se enviaron a una PON con un relación de división de 1:64. En la ONU un filtro sintonizable basado en óptica de Fourier de espacio libre selecciona una de las longitudes de onda que transporta servicios fijos y un filtro basado en redes de difracción de Bragg (FBG) extrae la longitud de onda que transporta servicios inalámbricos. En el enlace de subida se utilizó multiplexación por división de subportadora (SCM) para el transporte combinado de señales en banda base e inalámbricas a la oficina central (CO).

Palabras clave: Asignación Dinámica de Longitudes de Onda, Apilamiento WDM, Convergencia fija-inalámbrica, Filtros Ópticos, Redes de Acceso.

1. Introduction

High capacity optical access networks providing high bandwidth and reliable services to fixed users can also be exploited to deal with the transport of wireless services. Such hybrid architecture might emerge as a viable access solution where the optical network provides flexible high capacity backhaul to mobile end users [6-9]. To date, several approaches for converged transport of wired and wireless services in optical access networks have been proposed. A study on the effects of simultaneous wired and wireless transmission on fiber is discussed in [10], an analysis on the optical mobile backhauling is presented in [11] and a discussion on the requirements posed on the optical network technologies from the cellular mobile network is presented in [12]. Recently, a study dealing with the optimized placement of base band units acting as hotels that group several remote radio heads in a converged WDM access network was discussed in [13] and [14] described a view on the evolution of radio access

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networks supported by WDM exploitation in an already deployed infrastructure.

On the other hand, different approaches regarding dynamic capacity allocation have also been proposed. In [15], a remote node based on the combination of an optical switch and an Arrayed Waveguide Grating (AWG) enables the dynamic wavelength assignation among different ONUs, also active routing using Semiconductor Optical Amplifiers (SOA) have been proposed as a solution to dynamically distribute wavelength channels in the access network [16-18]. Consequently, it is clear that fixed and mobile convergence has become a hot topic in the optical networking field, in this context Radio over Fiber (RoF) systems technologies will enable combined transport of fixed and mobile users in the future access networks [19], [20]. As seen, advanced features such as dynamic capacity allocation and capacity upgrade have been proposed based on improvements performed on the remote node or point of wavelength distribution. Such enhancement involves the use of active components that are highly sensitive to polarization and leads to precise control and maintenance of it. Therefore, the challenge is to enable convergence and dynamic wavelength allocation among some other characteristics in an already deployed infrastructure, where the high bandwidth provided by the optical fiber and the ubiquity and flexible connectivity of the wireless access can be merged in a unified optical access platform. To address such requirements, namely, the increment of capacity, dynamic convergent wired and wireless access networks, load balancing and resilience while enabling a seamless way to evolution over the next years by reusing the current fiber infrastructure, a dynamic optical access platform based on a novel (CO) architecture that performs the wavelength stacking of several TDM-PON systems has been proposed and experimentally demonstrated.

2. Materials and methods

2.1. Architecture description

The approach for a wavelength stacked access network featuring dynamic wavelength allocation and convergent wired-wireless traffic in both CO and ONU is depicted in Fig. 1. In the CO, four wavelengths, 0.8 nm spaced, are multiplexed and broadcasted by means of the combination of a passive matrix and an Arrayed Waveguide Grating (AWG). This arrangement allows the even and low loss distribution of the four wavelengths between several PONs. An optical switch placed between the wavelength feeder and the AWG provides dynamic wavelength assignment for wireless distribution and capacity upgrade purposes. In particular, for the wireless traffic, a set of wavelengths denoted as (λ_x') use the next upper Free Spectral Range (FSR) of the AWG, these wavelengths are assigned individually depending on the demand to each one of their peers (λ_x) at the wavelength feeder. As a result, they are also broadcasted to each one of the ONUs enabling a converged platform for the distribution of wireless signals and with the capability of adding up to 4 wavelengths for overlay wireless traffic. For capacity upgrade of the wired traffic, an extra wavelength common to all the ONUs is mapped to an input port of the AWGs resulting in a selective capability to upgrade capacity among different ONUs. Inset (a) in Fig. 1 shows the downstream wavelengths: four fixed, one extra-wavelength and one wavelength for wireless transport. After fiber transmission and distribution, the downstream signal reach the ONU where an optical coupler splits the signal in two in order to recover the wireless and wired wavelengths respectively. For the wireless traffic a tunable Fiber Bragg Grating (FBG) filters out from the downstream signals $\lambda_{x'RF}$, whereas for the wired data, a tunable free-spaced Fourier optics (FSFO) based optical filter selects one from four possible wavelengths (λ_x). In both cases, the wavelength allocation is dynamic as each ONU can be assigned with different wavelength channels depending of the traffic load on the network. Inset (b) depicts the architecture of the ONU. In the upstream, all the users share the same wavelength and both wired and wireless traffic is transported using subcarrier multiplexing (SCM) as seen in inset (c). Wireless and wired signals are electrically multiplexed. Direct modulation and Time Division Multiple Access (TDMA) are considered for the uplink connection. In the uplink, in order to avoid carrier suppression effects a FBG removes one of the sidebands of the upstream signal as seen in the spectrum shown in inset (d).

Subsequently down conversion of the wireless subcarrier and direct detection of both wired and wireless signals are performed. Overall, the presented architecture exploits the WDM stacking to enable the deployment of PON based access networks featuring converged transport and dynamic allocations of resources.

2.2. Implementation details

For the experimental demonstration, continuous wave (CW) laser sources generating four wavelengths spaced 0.8 nm with an average modulated optical power of 15 dBm were used at the wavelength feeder. The four fixed wavelength channels were $\lambda1$ = 1546.64 nm, $\lambda2$ = 1547.44 nm, $\lambda3$ = 1548.24 nm and $\lambda4$ = 1549.04 nm. The extra wavelength λ-Extra is centered at 1549.86 nm and λ-RF is 1553.08 nm which correspond to the next upper FSR of the 1X8 AWG. The four multiplexed wavelength channels for wired services convey 10 Gb/s traffic Non Return to Zero (NRZ) encoded and the wavelength for the transport of wireless services conveys 10 MBauds, 16QAM modulated onto 5 GHz. For the uplink, all the ONUs share the same wavelength centered at 1532.7 nm that conveys SCM-combined 2.5 Gb/s and 5 MBauds 4QAM modulated onto 5 GHz. The passive matrix is intended to distribute a wavelength channel between different PONs, for demonstration purposes the wavelength channels were directly multiplexed through a gaussian band-pass profile 1X8 AWG with roughly 3 dB insertion losses. A circulator allows the use of a single strand of fiber for bidirectional transmission.

The optical circulator accounts for insertion losses of approximately 0.7 dB. After 20 km of optical transmission through Standard Monomode Fiber (SMF) and a 1:64 splitting ratio, the measured losses were close to 25 dB. FBG filters featuring a bandwidth of 20 GHz were used to separate the wavelength channel that transports the wireless data $\lambda_{x'RF}$. While a stretching mechanism enabled FBG tunability to λ-RF, thermal control as described in [21] was used to assure stable operation on this wavelength. For demonstration purposes the fixed channels were recovered by using a bulk tunable (FSFO) filter with a band-pass of 25 GHz. It should be pointed out that other filtering technologies such as Fabry-Perot filters or FBG can be used; however the FSFO filter provided more flexibility to the experimental demonstration as it allowed changing the band-pass width.

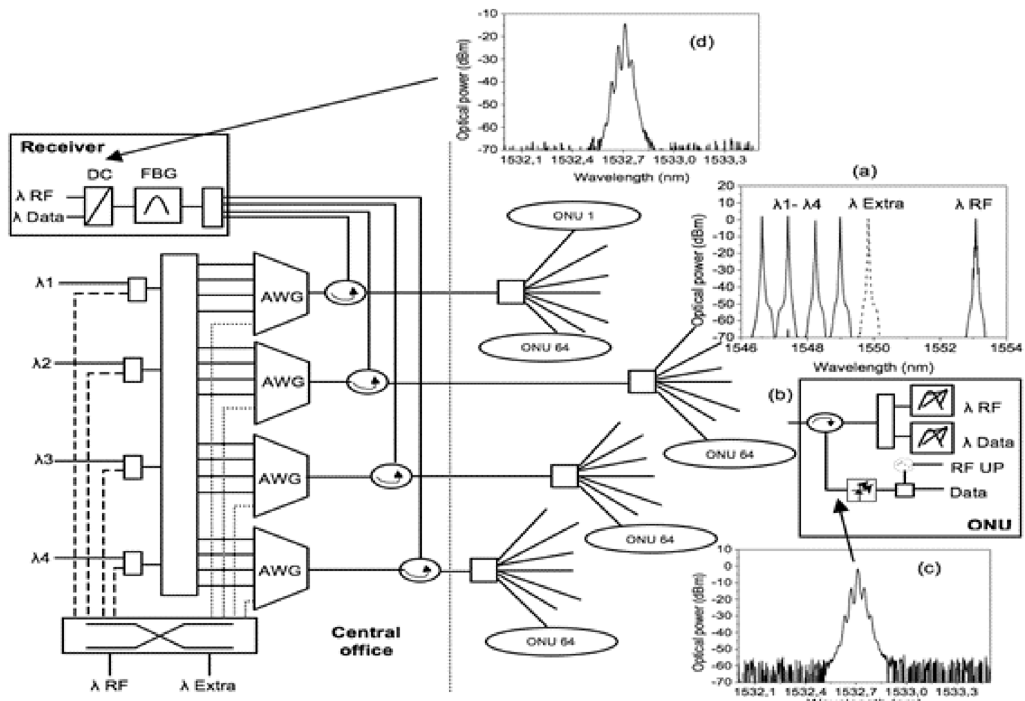

Figure 1. Layout of the wavelength stacked approach featuring dynamic allocations of wavelengths for wired and wireless services
Source: The Authors

3. Results and discussions

Fig. 2 depicts two different scenarios demonstrating the operation and feasibility of the proposed architecture. Each scenario shows the wavelength channel selection in ONU's belonging to different PONs. Scenario 1 shows the wavelength allocation in ONU 1 at four different PONs. PON 1 has been assigned with λ1, PON 2 with λ4, PON 3 and PON 4 with λ2. In scenario 2, λ4 is allocated to PON 1, λ1 to PON 2, PON 3 is assigned with λ-Extra due to the high load of the other wavelengths at that time and λ3 is allocated to PON 4. Finally, λ-RF is allocated to all ONUs in the four PONs. The signal degradation for the downlink and uplink was measured for wired and wireless services.

For the experimental evaluation, the quality of signals in ONU 1 and ONU 64 in four different PONs were measured under a dynamic wavelength allocation environment following the two scenarios described above.

Fig. 3(a) shows the Bit Error Rate (BER) performance of the examined wired services showing in all cases a penalty of approximately 2 dB for $1x10^{-12}$ BER compared to the back-to-back curve. Fig. 3(b) shows the quality of the wireless services, degradation of the 16QAM signal was measured showing an Error Vector Magnitude (EVM) below 4 % for received optical powers above -24 dBm and with a degradation of roughly 0.5% compared to the back-to-back value. The observed low penalties are caused mostly by the inherent insertion losses of signal transmission through the fiber, the optical coupler based splitting and crosstalk from the adjacent channels in the filtering process at the ONUs.

The experimental results showing the quality of the upstream wired signal are shown in Fig. 4(a). We evaluated the upstream signals from four ONU's at different PONs. Overall, the full penalty was measured to be 3.7 dB for 1x10-12. Fig. 4(b) shows the results obtained from the upstream wireless service, the measured EVM is roughly 5% for received powers below -31 dBm and showing a degradation of 1.25% as compared to the back-to-back of the signal. The degradation of the uplink signals is caused by the crosstalk coming from the wired and wireless signal remains in the process of detection and down conversion respectively.

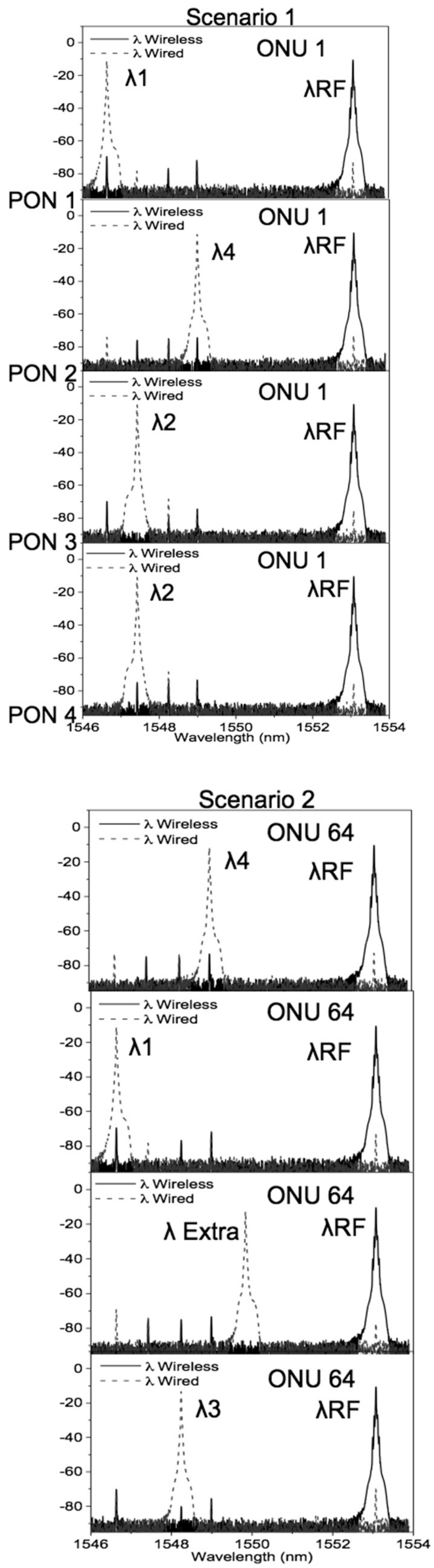

Figure 2. Experimental results. Scenarios of dynamic wavelength allocation in wavelength stacked access networks
Source: The Authors

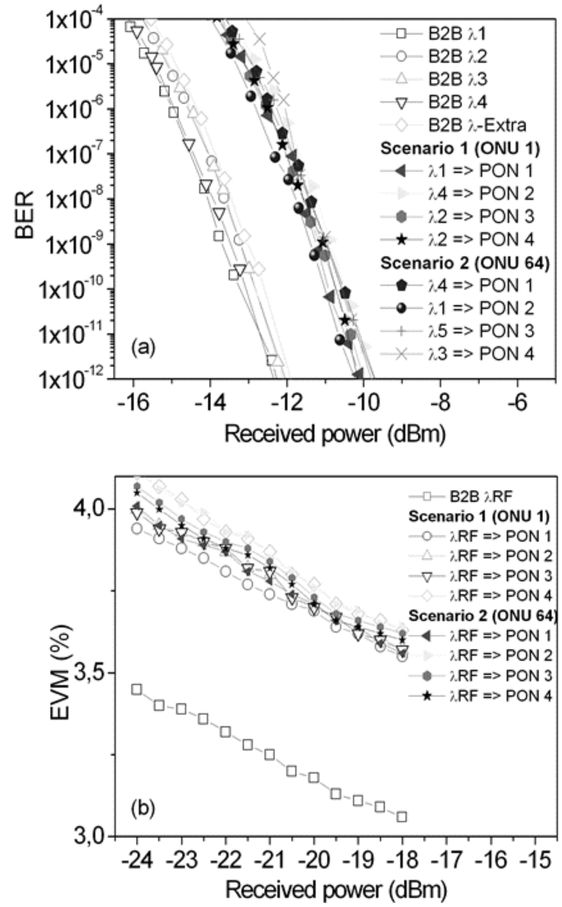

Figure 3. Experimental results. (a) Downlink BER. (b) Downlink EVM
Source: The Authors

Negligible quality differences were found in the uplink services coming from different PONs.

4. Conclusions

An optical architecture for converged transport of wired and wireless signals featuring dynamic allocation in multi-wavelength WDM-TDM PON access networks was presented. Four wavelengths for wired services 0.8 nm spaced common to all ONUs and one dynamically routed wavelength were broadcasted in the downlink direction. For the wireless services, up to four dedicated and common wavelengths to all ONUs can be used. Exploitation of the wavelength stacking paradigm to implement dynamic wavelength allocation, load balancing and capacity upgrade for converged transport while allow a seamless way to evolution by reusing the current fiber infrastructure constitutes the novelty and fundamental basis of this approach. This proposal aims at upgrading both the CO and ONU architectures in order to provide WDM connectivity between them. The fact that a stack of wavelengths are broadcasted from the CO to different PON may generate a potential limiting factor in the power budget due to the insertion losses imposed by the optical components placed at the CO and the high splitting ratio proposed. However, the power requirements can be relaxed by using high

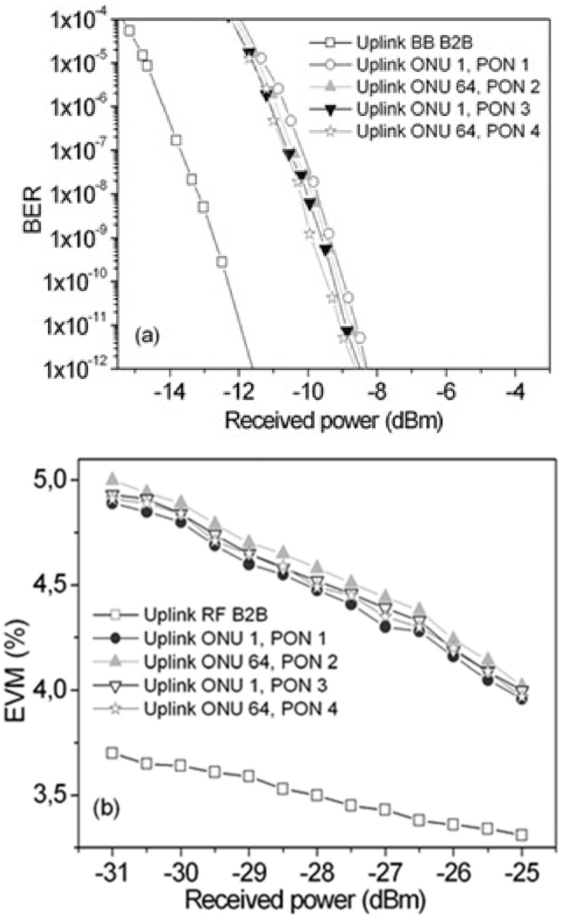

Figure 4. Experimental results. (a) Uplink BER. (b) Uplink EVM
Source: The Authors

sensitivity optical receivers at the ONU, typical values of commercial optical detector for PON applications ranges from -27 to -32 dBm. Therefore, the approach is feasible in terms of optical power as long as an appropriate power budget is assured by selecting the right optical devices to implement the CO and OLT.

As far as the dynamic WDM behavior, tunable filters are used to extract the wired and wireless wavelengths from the downstream channels; in particular a 20 GHz narrow FBG was used to filter the wavelength carrying the wireless services and a free spaced Fourier optics based filter featuring a bandwidth of 25 GHz was used to select one of the wavelengths carrying the baseband data. Regarding the tunable filters, so far no practical candidate technology can perform fast selection, while there are several technologies for slow selection, such as Fabry-Perot filters, thermally tuned semiconductor optical filters, FBGs or the used in the experiments based on free spaced Fourier optics. Therefore, further research is needed to implement wavelength-tunable optical filters featuring fast optical channel selection. As for the quality of the transported signals, the experimental measurements confirm the good performance of the system, 0.5% degradation for EVM and 2 dB penalties in average for $1x10^{-12}$ BER in the downlink whereas 1.25% degradation for EVM with 3.7 dB penalty in average for $1x10^{-12}$ BER in the uplink was measured.

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