Revista Ingeniería, Investigación y Desarrollo, Vol. 16 Nº 1, pp. (53-60), 2016

RECONFIGURABLE ARCHITECTURE BASED ON FIBER BRAGG GRATINGS FOR CONVERGENT OPTICAL INDOOR NETWORKS

(Arquitectura reconfigurable basada en redes de difracción de Bragg para redes convergentes indoor ópticas)

Gustavo Puerto Leguizamón[1], Wilson Ricardo López Sánchez[1], Carlos Arturo Suárez Fajardo[1]

[1]Facultad de Ingeniería, UDFJC. Grupo inv. LIMER, gapuerto@udistrital.edu.co
wrlopezs@correo.udistrital.edu.co, csuarezf@udistrital.edu.co
Universidad Distrital Francisco José de Caldas.

(Recibido agosto 29 de 2015 y aceptado octubre 15 de 2015)

Abstract
This paper presents an approach for dynamic reconfiguration of optical channels for future indoor network architectures. The approach exploits the tunability and the rejection profile of Fiber Bragg Gratings (FBG) to implement service distribution strategies that includes Unicast, Broadcast and Multicast scenarios for fixed and mobile users. Experimental demonstrations based on two implementations show results with 1% of average degradation for the Error Vector Magnitude (EVM) for the wireless services and power penalties of up to 2,2 dB for $1x10^{-12}$ Bit Error Rate (BER) for the wired services. In particular, the proposed architectures fit for large in-building networks.

Key words: Dynamic Channel Allocation, Fiber Bragg Grating, Optical Indoor Networks, Optical Filters.

Resumen
Este artículo presenta una propuesta para la implementación de reconfiguración dinámica de canales ópticos en futuras arquitecturas de red tipo indoor. La propuesta se basa en las características de sintonización y perfil de rechazo de Redes de Difracción de Bragg (FBG) para implementar estrategias de distribución de servicios de tipo Unicast, Broadcast y Multicast a usuarios en redes indoor tipo campus. La demostración experimental, que incluye dos diferentes implementaciones, muestra resultados con un 1% en promedio de degradación en la magnitud del vector de error (EVM) para los servicios inalámbricos y penalizaciones de potencia de hasta 2,2 dB de penalización para una tasa de error de bit (BER) de $1x10^{-12}$ para los servicios fijos.

Palabras clave: Asignación Dinámica de Canales, Filtros Ópticos, Redes de Difracción de Bragg, Redes Ópticas.

1. INTRODUCTION

Nowadays, optical networks are consolidating as the cornerstone that supports the high bandwidth in the core of Internet. Silica fibers enable long reach communications links with low attenuation and low delay at Terabit per second data rates. As the popularization of optical fibers continue to grow in the backbone core and metropolitan networks, other segments of the telecommunications networks such as the access and

The authors would like to acknowledge the Optical and Quantum Research Group of the Universidad Politécnica de Valencia and Universidad Distrital Francisco José de Caldas for supporting the realization of this paper.

the indoor sections have started to adopt the optical fiber as the preferred media to transport signals. In the access segment, recent worldwide deployments based on the Fiber to the Home (FTTH) paradigm featuring passive or active distribution have become a reality in replacement of legacy copper based access networks (Hanatani, 2013). With FTTH, the end user gets truly broadband connections to the core network. Lately, the interest has been put in deploying optical fibers in the segment closest to the user, the indoor network. Recent studies have confirmed the benefits in terms of CAPEX, OPEX and power consumption of the optical fiber as compared to traditional copper based Cat-5 cables (Koonen, Tran & Tangdiongga, 2011). As far as the topology is concerned, current indoor networks typically may run point-to-point (P2P) configurations in small buildings or point-to-multipoint (P2MP) in large indoor networks (campus) where a 100Base-SX or 100Base-BX fiber Ethernet modem allows the connectivity to Internet. These current indoor infrastructures are based on electro-optical and opto-electronic conversion (O/E/O) that leads to opaque networking. Opaque means lack of transparency to the signal format and bit rate, which makes difficult to upgrade the physical platform for new applications. On the contrary, when optical networking is used, wavelength channels can be setup and distributed transparently among different end users in the indoor network enabling a future-proof physical platform for future applications and bandwidth requests. By using this paradigm, transparent optical P2MP indoor networks can be deployed which in addition bring about improvements in the network efficiency by implementing the concept of routing optical channels directly in the optical domain to be exploited by the indoor segment.

In this context, multiple channels in the network allow the creation of multiple layers of interconnection inside the indoor network with each layer being supported by a separate wavelength (Koonen *et al.*, 2009). That is, each wavelength channel can now transport a different service. This feature open the way to a new set of interesting characteristics, feasible to be implemented in the indoor segment when reconfigurability is involved: separated providers, separated services, capacity allocation on demand and capacity upgrade. A reconfigurable architecture enables systems to dynamically select services or resources to satisfy changing requirements in the network. The approach is based on offering specific services to a given group of users in the indoor network by physical allocation of wavelength channels in accordance with a given demand. This paradigm can be exploited in scenarios featuring dedicated application service domains as those described in (ETSI, 2004; Jiang *et al.,* 2008; Olabarriaga *et al.*, 2010; Politi *et al*, 2012; Harbaoui *et al.*, 2012). Reconfigurable services can increase the selection space and significantly help with Quality of Service (QoS) assurance in all of these environments. To date, different approaches have been proposed with the aim of enabling wavelength dynamic reconfigurable indoor networks. In (Yang *et al.*, 2010) is presented the experimental study on dynamic capacity allocation in indoor radio-over-fiber networks using a semiconductor optical amplifier (SOA) featuring both optical and electrical routing. The blocking performance of an optical WDM-TDM indoor network under dynamic wavelength routing is presented in (Koonen *et al*., 2011). Similarly, in (Abraha *et al*., 2011) a service multicasting by all-optical routing of 1 Gb/s Impulse Radio-Ultra Wideband (IR-UWB) using Cross Gain Modulation (XGM) of SOA was demonstrated. Also, a Dynamic Distributed Antenna System (DDAS) based on a reconfigurable optical indoor network was presented in (Nguyen-Cac *et al.*, 2012). In this approach the radio signals are delivered to the remote antenna units by means of optical channels where dynamic radio sub-carrier assignment to the antenna units is performed by reconfiguring optical channels by means of optical gating procedures and optical multiplexing. In addition, two-stage optical routing in an indoor optical network using a SOA and integrated micro-ring resonator with remote generation of millimeter-wave signals by optical frequency multiplication was demonstrated in (Zou *et al.*, 2012). So far, complex systems based on active optical devices to enable dynamic wavelength allocation have been demonstrated. In spite of the ability of these systems to perform the target operations, most of the devices involved are highly sensitive to polarization that leads to precise control and maintenance. Another issue is the related cost of the physical platform when using such optical devices. This paper describes an implementation of an optical architecture to enable optical reconfiguration of wavelength channels for large single mode fiber based indoor networks. The architectures exploit the tunability and rejection characteristics of Fiber Bragg Gratings (FBG) filters to add reconfigurability to the wavelength distribution environment as well as advanced service distribution schemes such as unicast, broadcast and multicast functionalities for indoor environments featuring baseband and wireless services.

2. MATERIALS AND METHODS

2.1 Fiber Bragg Grating Description

A FBG is a periodic perturbation of the refractive index *n* along the fiber length. This perturbation generates a stop band in the frequency region in which most of the incident light is reflected back (Erdogan, 1997). The stop band is centered at the Bragg wavelength that is defined by:

$$\lambda_B = 2n\Lambda \quad (1)$$

Where Λ is the grating period and *n* is the average mode index. The periodic behavior of refractive index variations generates coupling of the forward and backward propagating waves at wavelengths close to the Bragg wavelength. As a result, the FBG provides a reflectivity that is frequency dependent to the incident signal over a bandwidth determined by the grating strength. This means that a FBG acts as a reflection filter. Stretching techniques or heating the FBG results in a change of the FBG period and so a change in the stop band, thus simple tunable filters are feasible to implement. For a FBG with period Λ, as described in (Erdogan, 1997), the effective refractive index of the core at a location *z* is given by:

$$n(z) = n_{eff}(z) + \delta_n(z)\cos\left[2\beta_0(z)z\right] \quad (2)$$

Where n_{eff} is the effective background refractive index of the fiber, $\delta_n(z)$ is the zero-peak amplitude of the spatial dependent effective refractive index modulation and β_0 is the propagation constant of the FBG as defined by:

$$\beta_0 = \frac{\pi}{\Lambda} \quad (3)$$

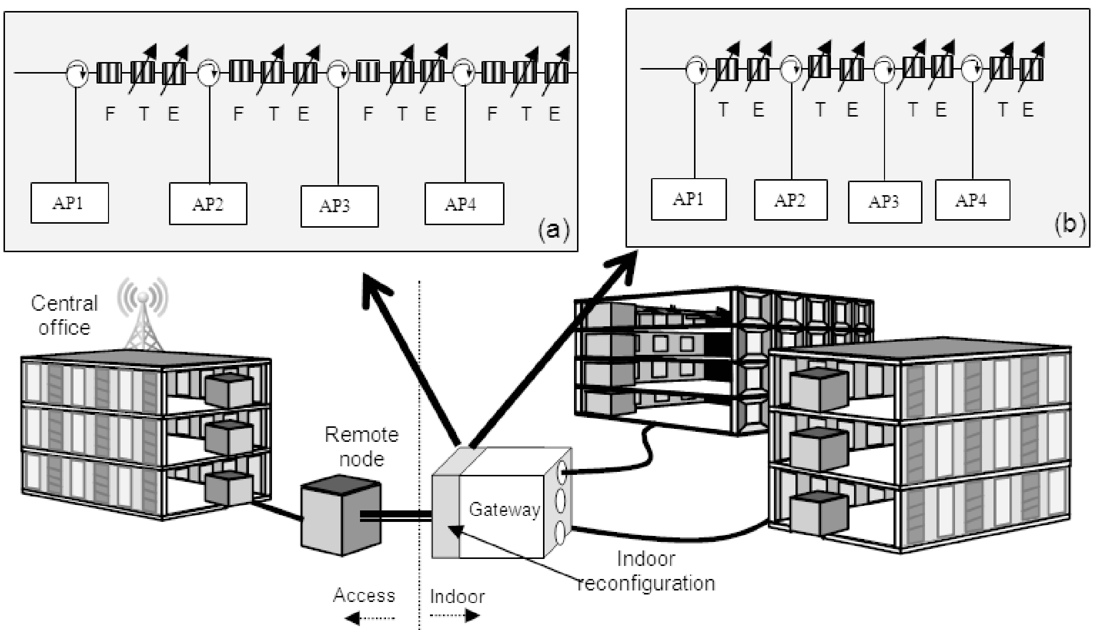

Figure 1. Reconfigurable architectures for indoor scenarios. (a) Featuring fixed (F), tunable (T) and equalized (E) FBG. (b) Featuring tunable (T) and equalized (E) FBG

Note that the effective refractive index, refractive index modulation depth and propagation constant have spatial dependence. This feature leads to an apodized FBG whose effect is to greatly suppress the out-of-band reflective peaks to provide a well-shaped narrow band filter (Hill et al., 1997). The analytical description of a uniform FBG yields to two particularly useful relationships (Erdogan, 1997), the maximum reflectivity R_{max} as a function of the coupling factor *k* and FBG length *L* as:

$$R_{\max} = \tanh^2(kL) \quad (4)$$

And the maximum reflectivity as a function of the band stop center frequency λ_B, the peak amplitude of the spatial dependent effective refractive index d_n, and the FBG length L as:

$$R_{\max} = \tanh^2\left[\frac{\pi}{\lambda_B}\delta_n L\right] \qquad (5)$$

2.2 Architecture Description

Figure 1 shows the proposed implementations and targeted environment for reconfigurable services.

In this approach the reconfigurable architecture makes part of the gateway where all the downstream services coming from the access network are classified and assigned to different wavelengths to be distributed accordingly in the indoor segment. Subsequently, the operation is based on the demultiplexing and routing of wavelength channel services as described in (Puerto *et al.*, 2010). The underlying difference in this approach lies in the switching technique. In this paper we propose to tune the FBG to the targeted channel, which then will be dropped to a given Access Point (AP) via an optical circulator. Figure 1(a) shows the first implementation, the system consists of a tandem of three FBGs per AP: one fixed FBG (F), one tunable FBG (T) and one equalized FBG (E). The fixed FBG assures one fixed channel per AP, this channel can be used for general purposes in the indoor network. The tunable FBG enables channel dropping to the targeted AP demand whereas the equalized FBG enable multicast functions. For equalization we mean that different FBGs have different rejection profiles in such a way that the same wavelength channel can be dropped out by different APs by reflecting a portion of the optical power of such wavelength while allows the transmission of the remaining power. The rejection is a measure of the transmission null depth at the center of the stop band. In addition, the equalized FBG can also be tuned in order to offer more flexibility to the multicast operations. To obtain such performance, the rejection profile *r* for the (*i*+1) FBG is given by:

$$r(i+1)[dB] = 10\log\left[1-\left(\frac{1}{n-i}\right)\right] \qquad (6)$$

Where *n* is the number of APs and 0<*i*<*n*-1. For instance, the equalized rejection profile to feed five APs is 0,97; 1,25; 1,76; 3 and 30 dB respectively. The operation of the implementation shown in figure 1(b), slightly differs from the previous one as no fixed service is assumed to be distributed to each AP apart from the on-demand dynamic reconfigurable wavelength services. In general, both implementations enable the characteristics above mentioned related to capacity upgrading, separate providers, allocation on-demand and service distribution in dedicated application domains. The underlying concept relies on the channel switching enabled by the FBG tunability. Thus, the use of one of these approaches in particular will strongly rely on the type of network and transported applications.

3. RESULTS

This section describes the evaluation scenarios and obtained results. Both implementations incorporate apodized FBG featuring 25 GHz of bandwidth. The architectures have been evaluated under different application scenarios aiming at demonstrating the routing capability of wavelengths based on the FBG tunability to enable broadcast and use of different rejection profiles in different FBG to enable multicast.

Figure 2 shows two scenarios respectively with the FBG responses enabling a switching state for two access points corresponding to the implementation shown in figure 1(a). Figure 2, left, shows the response for the switching state corresponding to the assignation of F1, T1 and E1 for AP1 and F2, T3 and E1 for AP2. Note that while the rejection values for F1 (unicast) and T1 (broadcast) are 16 dB and 20 dB respectively, in accordance with the rejection values derived from the equation (6) for the equalized (E) FBGs (multicast), the values for two APs are 3 dB and 30 dB. Figure 2, right, shows the scenario corresponding to the routing of F1, T2 and E2 for AP1 and F2, T1 and E2 for AP2. The rejection values for the fixed, tunable and equalized FBGs can be observed in figure 2.

Different services were deployed in order to evaluate the performance of the service distribution system. In particular, for the fixed channels a converged wireless and wired signal conveying baseband services at 2,5 Gb/s and RF services onto 5 GHz transporting 10 Bauds QPSK were used. The two channels were broadcasted in 1539,6 nm and 1540,4 nm respectively. Two multicast services were transmitted on 1545 nm and 1545,8 nm conveying baseband at 625 Mb/s and 2,5 GHz with 5 Mbauds-QPSK respectively. Finally, tunable services were transmitted on 1542,6 nm, 1543,4 nm and 1544,2 nm. These wavelengths carry a baseband service at 2.5 Gb/s, a RF service onto 5 GHz conveying 10 Mbauds QPSK and another baseband service at 625 Mb/s respectively.

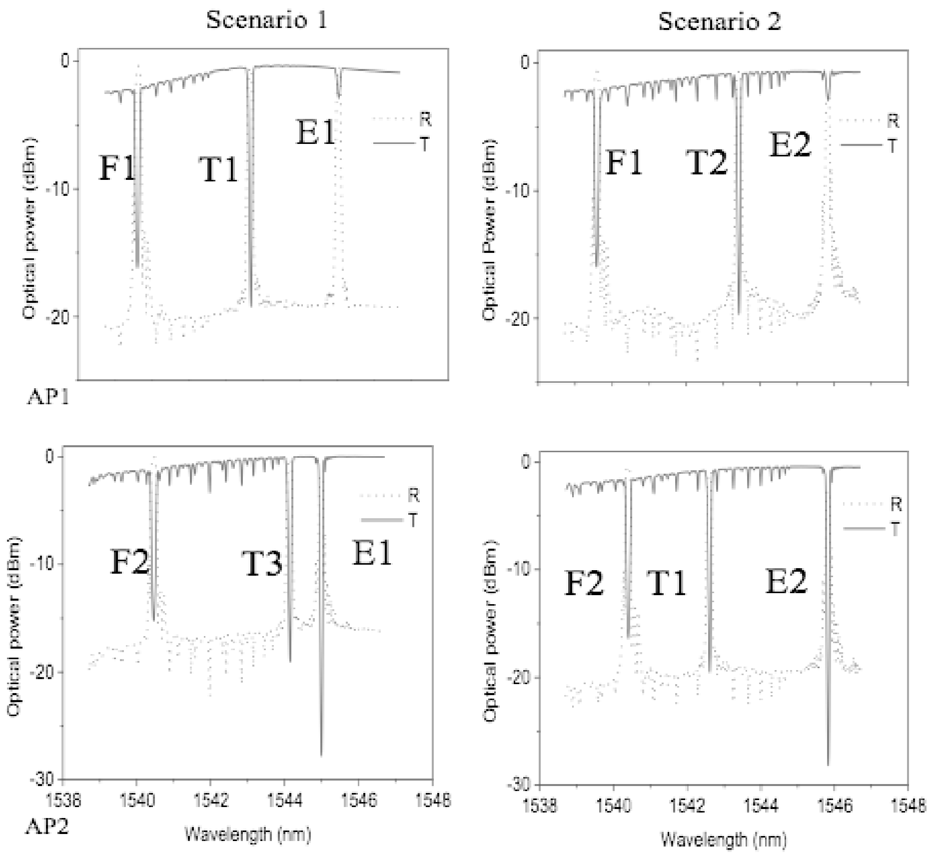

Figure 2. Experimental results. FBG responses for two access points featuring fixed, tunable and equalized FBGs in two different scenarios

After distributing the wavelength services the output powers to AP1 were 5,5; 5,5 and 7 dBm for F1, T1 and E1 services respectively whereas for AP2 the output powers were 6; 6,3 and 8 dBm for F2, T3 and E1 services respectively. While similar output powers were measured for fixed and tunable channels in both APs, noticeable differences were found in the multicast channels due to the cumulative effect imposed by the optical circulators. In order to assess the system performance, figure 3 shows the signal degradation for the above-described scenario. Degradation of the QPSK signal was measured in the respective AP showing a low Error Vector Magnitude (EVM) below 4,5 for received optical powers under -24 dBm and with a degradation of roughly 1% compared to the back-to-back value. The multicast service at AP2 underwent a higher penalty (0,5% higher as compared to value obtained at AP1). This is due to the unbalanced power imposed by the optical circulators.

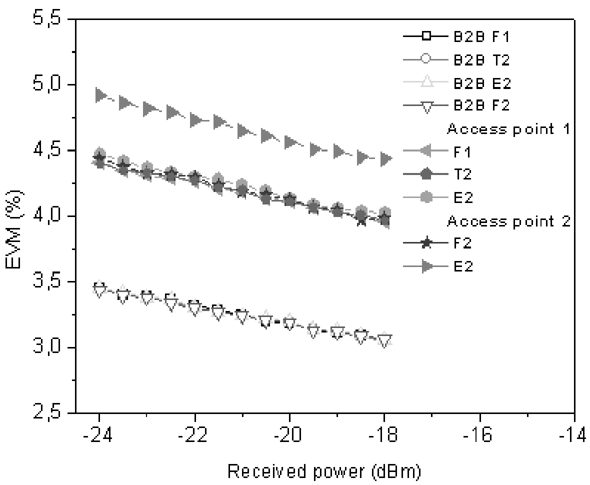

Figure 3. Signal degradation for the channels dropped by AP1 and AP2 featuring RF services

Figure 4 shows the Bit Error Rate (BER) performance on the examined digital baseband showing a penalty of 1,5 dB for $1x10^{-12}$ BER compared to the back-to-back curve. In this case the penalties were similar in both APs and were caused mostly by the inherent insertion losses of the system components.

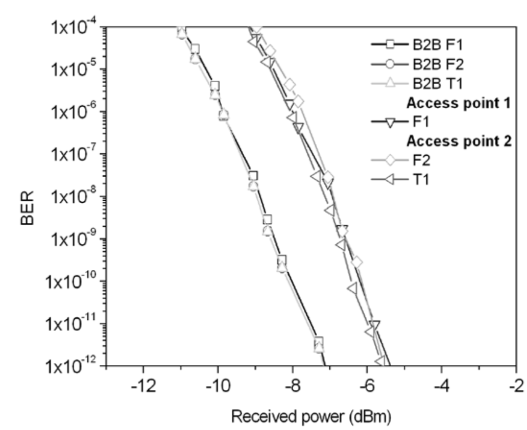

Figure 4. Signal degradation for the channels dropped by AP1 and AP2 featuring baseband services

As far as the implementation shown in Figure 1(b) is concerned, figure 5 shows the FBG response following two different scenarios and featuring three access points. Figure 5, left, shows the responses for T1 (broadcast), E1 (multicast) in AP1, T2, E1 in AP2 and T3, E1 in AP3 whereas figure 5, right, shows the switching state featuring T2, E2 in AP1, T1, E2 in AP2 and T3, E2 in AP3. Note the rejection profile of the equalized FBGs, following the results obtained from equation (6), for three APs the rejection values are 1,76; 3 and 30 dB respectively. To evaluate this implementation fixed and wireless services were transmitted on 1542,6 nm, 1543,4 nm and 1544,2 nm and carried baseband at 2,5 Gb/s, a RF service onto 5 GHz conveying 10 Mbauds QPSK and second baseband service at 2,5 Gb/s respectively. Similarly, two multicast services were transmitted on 1545 nm and 1545,8 nm conveying modulated baseband at 2,5 Gb/s and a RF service at 2,5 GHz with 5 Mbauds-QPSK respectively.

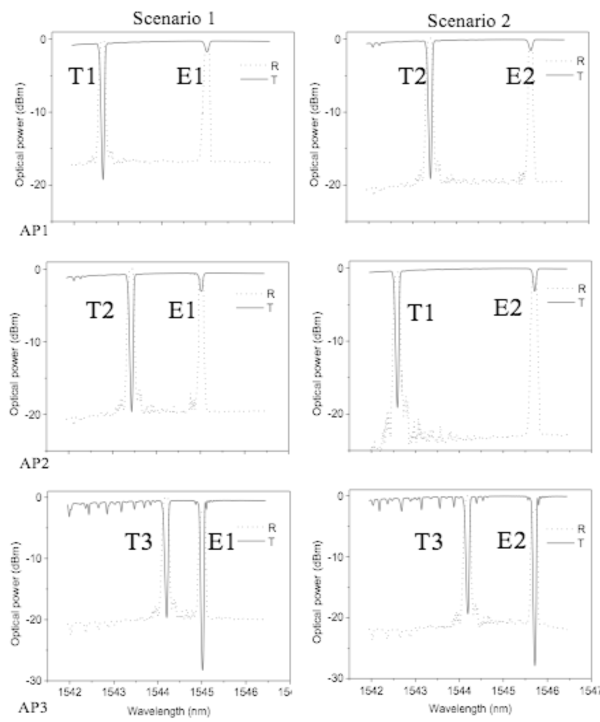

Figure 5. Experimental results. FBG responses for three access points featuring tunable and equalized FBGs in two scenarios

Figure 6 shows the signal degradation for the above-described scenario. Degradation of the RF service was measured in the respective APs showing an EVM below 4,4 for received optical powers under -24 dBm featuring a penalty of 0,95% compared to the back-to-back curve and with no noticeable difference between the quality in different APs as can be seen on the upper graph of figure 5. In this scenario the lack of a balanced power imposed by the optical circulators causes a BER performance penalty of the baseband service of 1,8 dB, 2,3 dB and 2,9 dB for 1x10^-12^ BER in AP1, AP2 and AP3 respectively as shown in the bottom graph of figure 6.

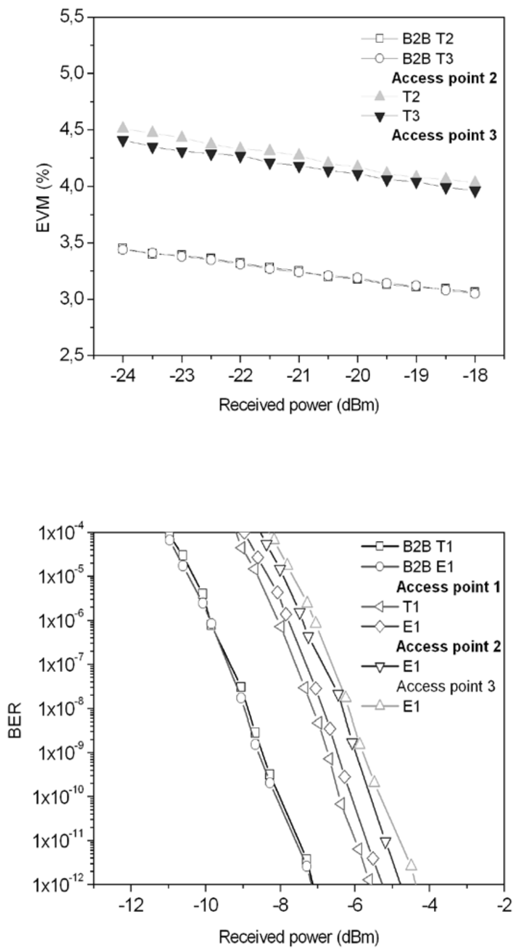

Figure 6. Signal degradation for the channels dropped by AP1, AP2 and AP3 featuring RF and baseband services

4. CONCLUSIONES

An approach to offer specific services to a given group of users in the indoor network with Unicast, Broadcast and Multicast transmission schemes was presented. The architecture derives reconfigurable wavelength strategies that result in capacity upgrades, allocation on-demand and dedicated application service domains. To these effects, two optical implementations of tunable network nodes to enable the above-mentioned capabilities in large in-building networks were demonstrated. The approach makes use of the tunable characteristic of the FBGs to perform the routing of wavelength services to different access points (AP) while distributes multicast services by exploiting the FBG rejection profile. Different wireless and baseband services have been successfully routed through different APs with no noticeable degradation effect on the transported signals and including the distribution of multicast services. 1% average degradation for EVM and power penalties of up to 1,8 dB for $1x10^{-12}$ BER values in non-multicast capable optical channels were measured while higher penalties (1,5% EVM for wireless services and 2,2 dB penalty for $1x10^{-12}$ BER baseband services) were found in the multicast optical channels due to the cumulative insertion losses imposed by the optical circulators.

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