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Optical Switching for Dynamic Distribution of Wireless-over-Fiber Signals in Active Optical Networks

J.J. Vegas Olmos, G. Rodes, and I. Tafur Monroy

Abstract— In this paper, we report on an experimental validation of dynamic distribution of wireless-over-fiber by employing optical switching using semiconductor optical amplifiers; we also provide a channel distribution scheme and a generic topology for such optical switch. The experiment consists of a four wavelength division multiplexed (WDM) channel system operating on a WiMax frequency band, and employing an orthogonal frequency-division multiplexing (OFDM) modulation at 625 Mbit/s per channel, transmission of the data over 20 km of optical fiber, and active switching in a one-by-sixteen active optical switch. The results show a negligible power penalty on each channel, for both the best and the worst case in terms of inter-channel crosstalk. The presented system is highly scalable both in terms of ports count and throughput, a desirable feature in highly branched access networks, and is modulation and frequency band independent.

Index Terms— optical access network, active optical network, radio-over-fiber, WiMax, wireless-over-fiber, semiconductor optical amplifier, optical switch.

I. INTRODUCTION

The ever growing demand of bandwidth by end users has put a lot of pressure on access networks, triggering the adoption of fiber systems in access almost two decades ago [1]. Depending on the requirements and features of the end users in terms of latency, quality of service (QoS) or service layer agreements (SLA), optical access networks have evolved in different directions [2]: high capacity at low price is supported by passive optical networks (PON) while quality assurance and security are supported by active optical networks (AON) [3].

Vendors and operators are now turning their eye to new markets where optics can be used effectively. Mobile backhaul is a target market [4], since mobile traffic is growing exponentially – new gadgets along with killer applications are fueling such growth. Baseband technologies can support mobile backhaul effectively at current rates. However, due to the location of new license-free available frequency bands and the development of radio-over-fiber (RoF) technologies – allowing generation, distribution and reception of micro- and millimeter wave band signals optically, migration towards wireless-over-fiber scenarios are likely [5][6]. Traditional constraints of RoF systems such as highly linear requirements for the modulator and chromatic-dispersion induced power fading during transmission are by now manageable. In any case, there is a general consensus about the exponential growth of mobile data traffic: CISCO's white paper on traffic forecast predicts a 26-fold increase of global mobile data traffic between 2010 and 2015 and a 10-fold increase in the average mobile network connection speed [7].

We hence need to provide solutions capable of effectively handling wireless-over-fiber signals regardless their nature in terms of frequency operation, modulation format, bitrate and so on. Furthermore, the system must be able to scale graciously in terms of channels and capacity, allowing for future upgrades in terms of wireless technologies. These requirements set a new range of challenges in the field of RoF, such as multi-channel operation, extended reach, extreme performance limits (including linearity, especially in optical components), cost issues related to the deployment of millimeter wave equipment in the field and architectural limitations [8]. Current state-of-the-art research on RoF have shown that high-capacity radio signals can be generated, transmitted and successfully recovered at high frequency bands, such at 60 GHz and 75-110 GHz band [9], even over long distances [10].

However, these demonstrations are limited to static distribution of RoF signals, and neglect the dynamism required in mobile-supporting networks, which is achieved through switching. Previous demonstrations of RoF switching included a WiMAX-over-fiber demonstration for a high speed train system [11], but the scalability was limited and the throughput less than few Mbit/s, and a passive distribution of twelve WiMax signals operating at 2.6 GHz [12]. Technologies demonstrating optical switches for RoF have also been presented, such a 3D microelectromechanical system (MEMS) for in-building networks [13], a SOA-based switch with reduced scalability

[14] and wavelength packet switch based on distributed Bragg reflectors [15].

In this paper, we propose to employ a one-by-sixteen active switch based on semiconductor optical amplifiers (SOAs) and arrayed-waveguides (AWGs) to provide fast switching for wireless-over-fiber systems, enabling novel unicast and multicast distribution. The employed optical switch, originally designed for high capacity interconnects, enables quick reconfiguration and selective-delivery, hence going one step beyond up-to-date reports on optical switching for RoF signals. Furthermore, the optical switch is modulation format independent, permitting to use it with different wireless technologies at different frequency bands. Specifically, we demonstrated four WDM channel switching after transmission through 20 km of standard single mode fiber (SSMF), which equals the length of a traditional PON. The RoF signals emulated WiMax signals by being set to operate at the 5 GHz frequency band, employing orthogonal frequency-division multiplexing (OFDM) and operating at 625 Mbit/s.

The paper is organized as follows: Section II introduces the system architecture, technologies for switching and the optical switch employed in this research. Section III presents the experimental setup and a characterization of the switching elements. Then, quantitative results in terms of bit error rate (BER) are presented in Section IV. Finally, conclusions and further work are given in Section V.

II. System Architecture and Design Choices

This section describes the advantages of an AON system used for wireless-over-fiber delivery employing RoF technologies, technologies for optical switching, and then introduces the optical switch employed during the experimental assessment.

A. Active optical network and radio-over-fiber

PON systems have become very popular during the last lustrum because they offer both low capital and operational expenditures, which are critical factors in access networks. In fact, less than a decade ago, PON and AON systems had a similar market share. It is now becoming obvious that PON efficiency is however low in terms of bandwidth utilization and power budget issues limit the splitting ratio and the attainable link lengths. Furthermore, the intrinsic nature of the distribution approach (point-to-multipoint multicast) may raise concerns in terms of security, especially in industrial or business environments. AON approaches are emerging back in this area to cope with such problems: data can be effectively managed at a traffic engineering level (i.e., path control, bandwidth reservation, prioritization, etc.), while ensuring secure unicast distribution and simple and flexible designs. When considering AON networks, in the context of wireless systems, the advantages are clear: we can better handle data distribution while preserving the mobile nature of the end users. Figure 1 shows a distribution system of wireless signals employing a consolidated central office (CO). A consolidated CO serves several clusters of access networks (either AON or PON networks) centralizing the

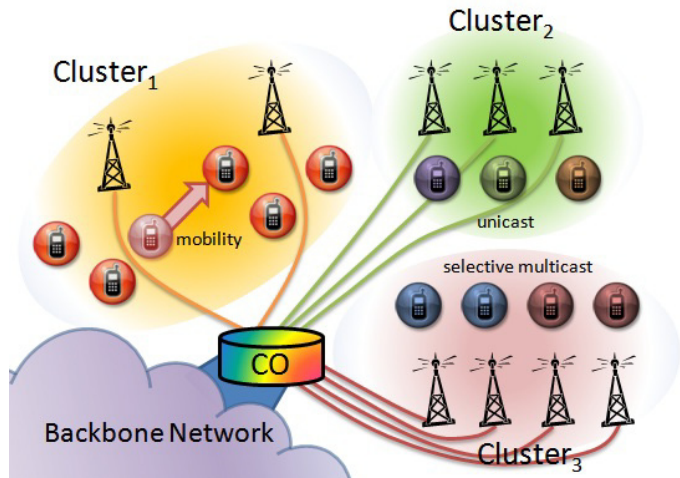management of the system and employing a single physical platform.

Fig. 1. General architecture of an active optical network for mobile applications, including unicast and selective multicast capabilities. CO: central office.

Furthermore, concerns on security [16] and high mobility [17] seem to indicate active solutions such AON may be in favor of system designers, provided that cost and energy consumption are maintained within reasonable limits. AON networks, in combination with RoF technologies, are hence an interesting way of enabling a higher degree of reconfigurability in scenarios in which the end user is mobile per se, and requires low-latency, high-throughput and physical layer security features.

B. Optical switches – technology of choice

All-optical switching fabrics play a central role in allowing switching in the optical domain, avoiding the need for O/E/O conversions [17]. There are a plethora of technologies used to construct complex optical switches (i.e. more than two output ports): optomechanical switches [18][19], MEMS [20], electrooptic switches based on lithium niobate (LiNbO$_3$) [21] or active vertical coupling [22], microring resonators [23], thermooptic switches [24], among others. Benchmarking and technical comparisons can be found analyzing the suitability of such technologies for optical switching [25][26]

All these fabrics are passive in nature, meaning that no gain occurs. Hence, there are inherent limitations in terms of scalability due to the decay of power when several individual switches are cascaded. Semiconductor optical amplifiers (SOAs) are promising alternatives as switch fabrics precisely because they can provide gain along with fast switching time [27].

C. Optical switch based on SOAs

The optical switch fabric employed to demonstrate active switching of RoF signals is based on a three-stage architecture, initially proposed for the optical shared memory supercomputer interconnect system (OSMOSIS) project [28][29]. The OSMOSIS interconnect is a broadcast-and-select optical switch fabric using SOAs, acting as on-off gates, and AWGs as filters. Such architecture was initially

intended for supercomputer interconnects, in which high-speed, low-latency and high-throughput are key. This optical switch can serve several clusters, each cluster being composed of several and identical wavelength channels; the clusters are orderly placed on the optical domain and processed independently. Figure 2 shows the wavelength allocation, consisting of N clusters, of M base stations (BSs) each.

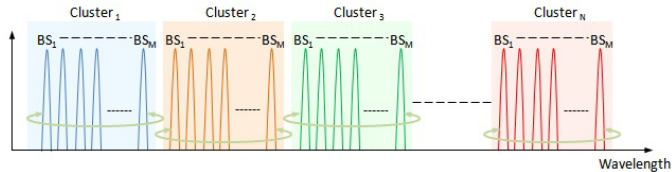Fig. 2. Wavelength allocation. Clusters 1-N comprise base station channels 1-M. BS: base station.
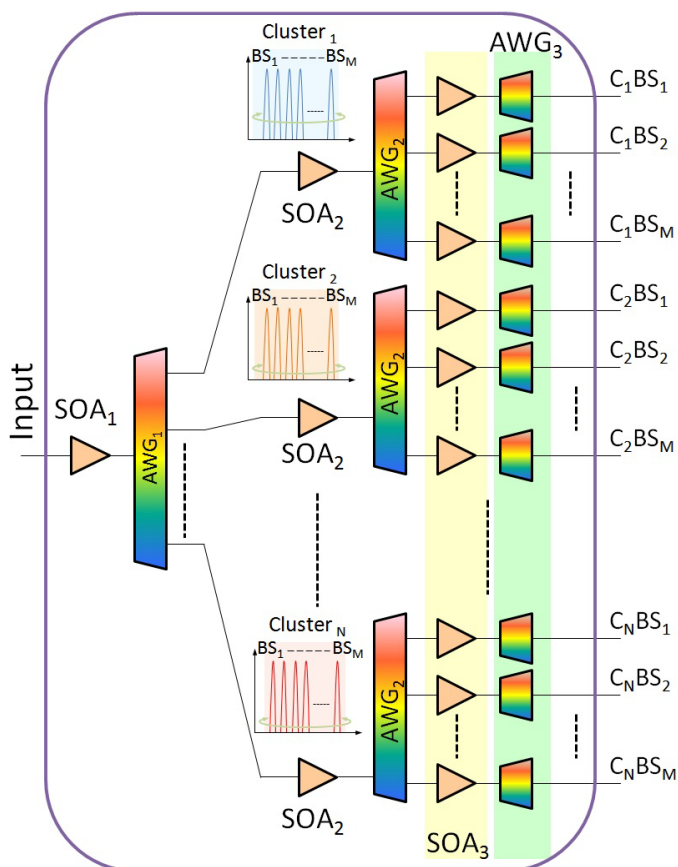

Fig. 3. Internal schematic of a generic switch. SOA: semiconductor optical amplifier, AWG: arrayed-waveguide, C: cluster, BS: base station.

Figure 3 shows the internal architecture of a generic switch fabric. The input of the optical switch conveys the spectra shown in Figure 2. SOA1 amplifies all the clusters while AWG1 separates the clusters. The second set of SOAs, namely SOA2, act as on-off gates for each cluster, which is further disassembled by the second set of AWGs, in this case AWG2. At this stage each channel has been already separated, and a final round of SOAs, SOA3, decides whether the channel must be fed into the BS through one last AWG. This last AWG acts as a filter to remove the amplified spontaneous emission (ASE) noise. In fact, the last AWG may have the same size as AWG2 with matching

wavelength features or be an independent AWG. Hence, the switch allows to unicast the channel to a single BS, or selective multicast the channel to the desired BSs by making use of the last round of SOAs. In the event of activating all the amplifiers corresponding to the SOA3 round, the system emulates in fact a conventional point-to-multipoint PON system. It is worth pointing out that the architecture and further experimental demonstration provided in this paper only deals with the downstream distribution; however, once the optical switch is demonstrated by backfeeding the upstream channels into the switch [30] or duplicating the switch to collect the upstream flows [31], a bidirectional system can be implemented based on the same technological solution.

Although the experimental demonstration conducted in the next section was done with discrete components, the proposed architecture can be photonically integrated, using for example active-passive InGaAsP-InP epitaxy as in [32]. Current technologies allow combined integration of passive and active components, drastically reducing the footprint and decreasing the power consumption of the active devices while preserving their features. Specifically, SOAs can be designed to operate at the desired wavelength ranges and gain levels. Furthermore, whereas employing SOAs for baseband signals has limitations in terms of bitrate due to the natural recovery time of the gain of the SOA (typically ~100ps) [31], RoF signals employing OFDM modulation are less likely to experience degradation due to this effect on the SOA because OFDM signals utilize a plurality of carriers to convey the data, effectively reducing the bitrate. SOAs are also fairly transparent to phase information, enabling their usage together with advanced modulation formats.

III. EXPERIMENTAL SETUP

Figure 4 shows the experimental setup. To emulate the schematic depicted in Fig. 3, four lasers operating at λ_1=1547.65nm, λ_2=1548.48nm, λ_3=1549.27nm, and λ_4=1550.12 nm, were combined and simultaneously modulated by a Mach-Zehnder Modulator (MZM) with a 5GHz OFDM quadrature amplitude modulation (4-QAM) signal with 128 subcarriers operating at 625 Mbit/s and a bandwidth occupancy of 312.5 MHz. The four channels were then transmitted through a 20 km of SSMF with approximately 6.5 dB of insertion losses, and then fed to the optical switch.
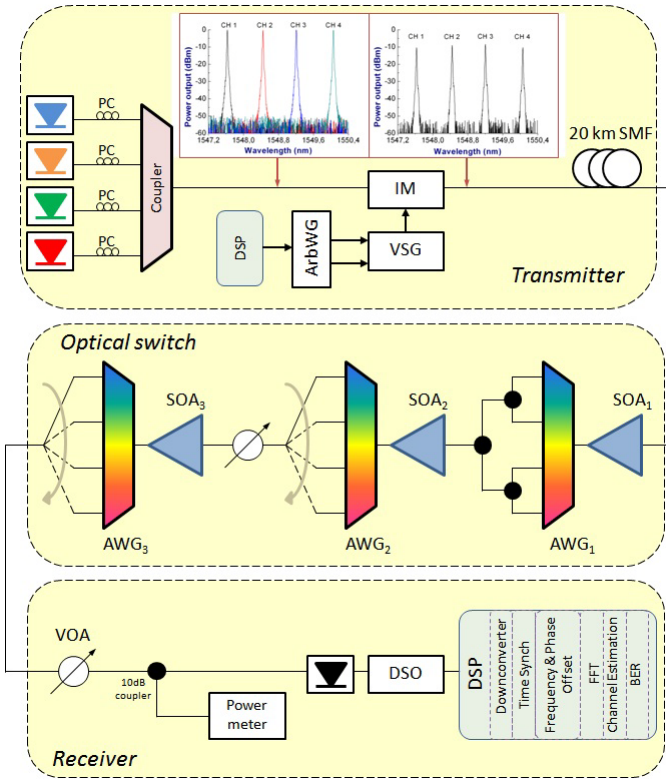
Fig. 4. Experimental setup. The insets show the optical spectra of the generated channels after being passively combined and also after modulation. PC: polarization controller, VSG: vector signal generator, ArbWG: arbitrary wave generator, DSP: digital signal processing, MOD: optical modulator, SOA: semiconductor optical amplifier, AWG: arrayed wave-guide, VOA: variable optical attenuator, DSO: data storage oscilloscope.

The SOAs employed in the experiment are characterized in Fig. 5. As it can be observed, the SOAs operate as attenuators when the bias voltage is less than 0.6 V, and as amplifiers when the bias is over 1.2 V. During the experiments, SOA$_{off}$ and SOA$_{on}$ were set by using Bias=0 V and Bias=1.8 V, respectively. The SOAs presented less than 0.5dB of polarization depending gain [34]. This resilience towards polarization variations allowed us to avert the use of polarization controllers before each amplifying stage. The switching time of the SOAs employed in this experiment has been reported to be less than 10ns [34]. The AWGs employed during the experiment matched the channel frequencies of the channels. The channel spacing of the AWGs was hence 100 GHz, matching the wavelength of the signals.

The four channels were fed into the optical switch, where they first experienced 10 dB gain through SOA1. The output of SOA1 was connected to AWG1. Since the experiment aims at emulating a single cluster with four channels, the filtered signals were recombined using 3-dB couplers, to emulate a 400 GHz AWG, not available in the lab. The signals were then fed into the second stage of the switch, consisting of SOA2 and AWG2, and then the third stage, consisting of SOA3 and AWG3. A variable optical attenuator (VOA) was introduced between the second and the third stage of the optical switch to avoid nonlinear effects due to saturation in SOA3. The dashed arrows at the

output of the second and third stage represent changes in the physical interconnection; such changes were done in order to assess if signals were effectively switched.

Each switched signal was then fed into a receiver block, consisting of a 10dB tap for monitoring, followed by a p-i-n photodiode, a digital sampling oscilloscope (DSO) operating at 40 GS/s and a digital signal processing (DSP) computational block to process off-line the stored data.
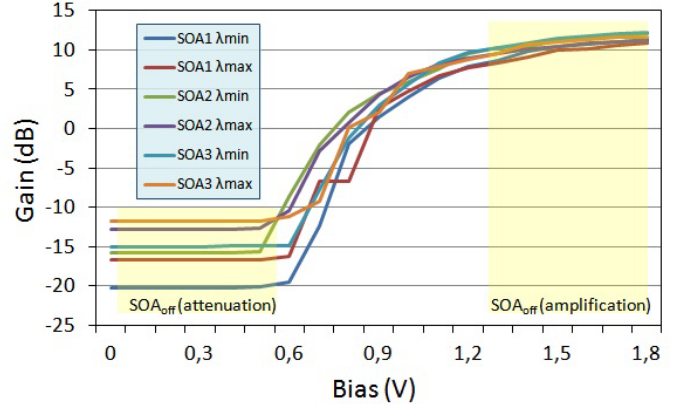

Fig.5. Characterization of the SOAs employed in the experiment, for two different wavelengths (λ_{min}=1546,8nm, λ_{max}=1555,7nm). The SOAs in the optical switch are operated either in the attenuation range (SOA$_{off}$→Bias=0V) or the amplification range (SOA$_{on}$→Bias=1,8V).

IV. RESULTS AND DISCUSSION

Considering the size of the optical switch and the number of channels, many output combinations can be set. During the experiments, we focused on the best and worst case scenario for each channel. The best case scenario corresponds to a unicast configuration in which a single channel is optically switched to the desired output port, while the rest of the channels are block by setting the last stage of SOAs (SOA3) off. The worst case corresponds to a multicast configuration in which the channel is broadcasted to all the output ports, by enabling all SOAs of the third stage. Figure 6(a) represents visually the best and worst case scenarios for Channel 1, illustrating the presence of signals at each stage of the optical switch. Figure 6(b) shows the recovered constellations for Channel 1, for the back-to-back and the worst case scenario (CH 1 B2B and CH 1 ON, respectively). As it can be observed, the penalty on the constellation is perceivable but exiguous.
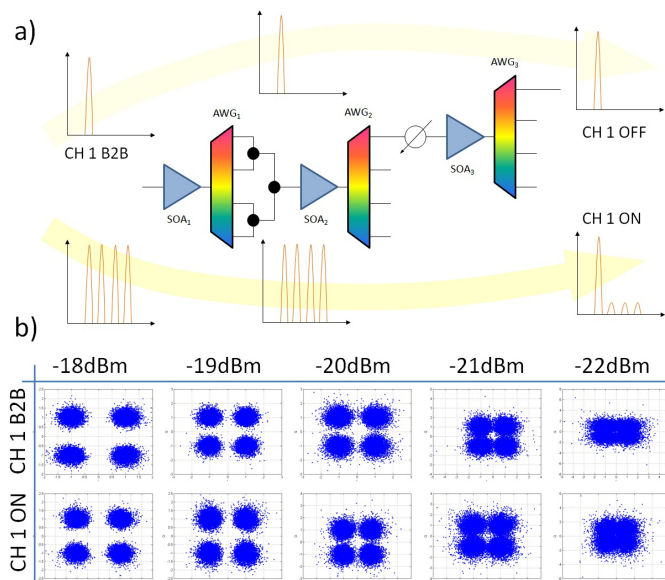
Fig. 6. A detail of the optical switch showing the presence of signals in the best case (CH1 OFF) and the worst case (CH 1 ON) (a), and plots of the constellations at the receiver side for CH 1 at different optical powers (b). SOA: semiconductor optical amplifier, AWG: arrayed wave-guide.

Figure 7 shows the BER performance of all the channels. As it can be observed, the back-to-back (b2b) performance is only slightly degraded (<0.5dB) when the channel is switched to the desired ouput in the best (OFF) and worst case (ON) scenarios, as the constellations in Fig.6(b) augured. This result was expected since, as described in Section II.b., SOAs are not expected to induce any phase or amplitude degradation to the signals operating in the experimental range. Impairments are most likely to occur in case of bitrates one order of magnitude higher. The optical switch allows switching RoF signals based on current commercial standards without impairing their performance.
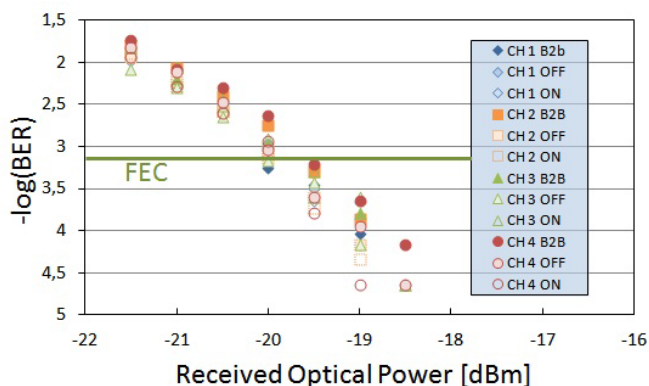

Fig. 7. BER performance of the system. The insets show the constellation of CH1 at the receiver side in the worst case scenario (rest of the channels ON). B2B: back-to-back, OFF: the other channels are set OFF by setting all SOA$_3$s OFF. ON: the other channels are set ON by setting all SOA$_3$s ON. FEC: forward error correction.

An initial concern when designing the switch with SOAs was the possibility of distortion due to nonlinear effects and

noise accumulation. The BER results indicate nonlinear effects have no impact on the signal, mainly due to the power levels handled by the switch; the signals are always maintained within the linear regime range of the SOAs. Noise accumulation, specifically ASE noise, plays a minor role thanks to the usage of AWGs, which filter any outband noise. Furthermore, since the RF signal has a frequency of only 5 GHz, fading effects due to dispersion during transmission are unlikely to occur.

V. CONCLUSION

An optical access network based on RoF technologies was presented and an experimental validation conducted. The experiment consisted in the implementation of a four channel system operating on a WiMax frequency band, and employing an OFDM-4QAM modulation at 625 Mbit/s per channel, transmission of the data over 20 km of optical fiber, and active switching in a one-by-sixteen active optical switch. The results reveal a negligible power penalty of less than 0.5dB on each channel, for both the best and the worst case in terms of inter-channel crosstalk. The novelty of this work lays in the utilization of a highly reconfigurable and scalable, modulation format independent, optical switch initially designed for optical interconnections for distribution of wireless signals in access networks. This has a direct impact on how to avoid the bandwidth crunch predicted in [7].

Future work includes assessing the impact of nonlinearities induced by the SOA when higher order modulation formats are used (i.e. 16-, 32-, 64-QAM), or degradation due to noise accumulation because of SOA concatenation for higher number of stages. Furthermore, a smart upstream collection system needs to be designed since networks are bidirectional in their nature.

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