

Optical Switching for Dynamic Distribution of Wireless-over-Fiber Signals

G.A. Rodes, J.J. Vegas Olmos, F. Karinou, I. Roudas, L. Deng, X. Pang, 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; the rest of the network was designed according to the channel distribution over the optical spectra required by the optical switch. An experimental validation was also conducted. 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.

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, 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]. 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.

Previous demonstrations of RoF switching included a WiMAX-over-fiber demonstration for a high speed train system [6], 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 [7]. 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. 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 passive optical network (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 and the optical switch. Section III presents the results obtained in terms of optical spectra. 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, 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 because they offer low-cost-per-bit on an optical fiber in terms of equipment and very low operational expenditures once they are deployed. PON efficiency is however low in terms of bandwidth utilization. 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 in this area to

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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.

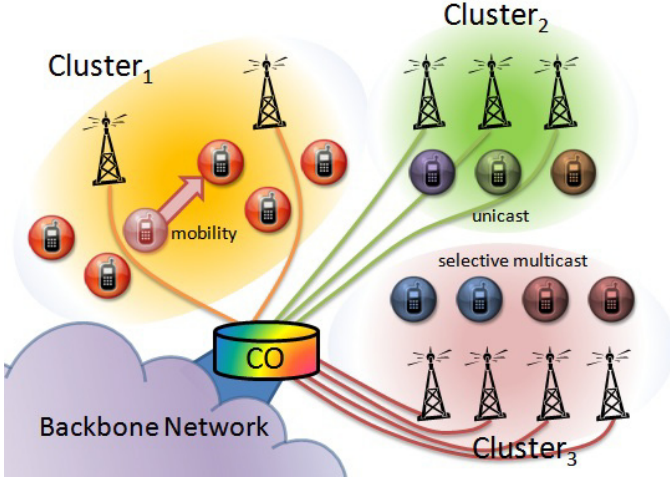


Fig. 1. General architecture of an active optical network for mobile applications, including unicast and selective multicast capabilities. CO: central office.

Furthermore, concerns on security [8] and high mobility [9] seem to indicate active solutions such as 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 L0 security features.

B. 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 [10][11]. 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.

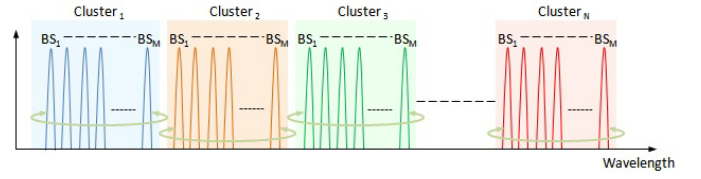


Fig. 2. Wavelength allocation. Clusters 1- N comprise base station channels 1- M . BS: base station.

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. 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.

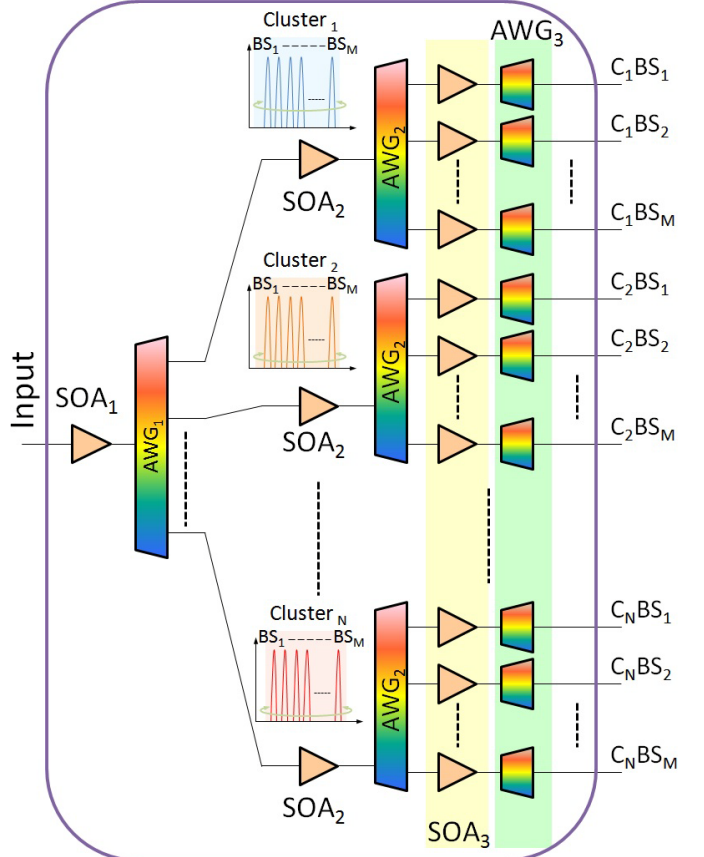


Fig. 3. Internal schematic of a generic switch. SOA: semiconductor optical amplifier, AWG: arrayed-waveguide, C: cluster, BS: base station.

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 [12]. 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 ~ 100 ps) [13], 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 $\lambda_1=1547.65$ nm, $\lambda_2=1548.48$ nm, $\lambda_3=1549.27$ nm, and $\lambda_4=1550.12$ nm, were combined and simultaneously modulated by a Mach-Zehnder Modulator (MZM) with a 5GHz OFDM quadrature amplitude modulation (4-QAM) signal operating at 625 Mbit/s. 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.

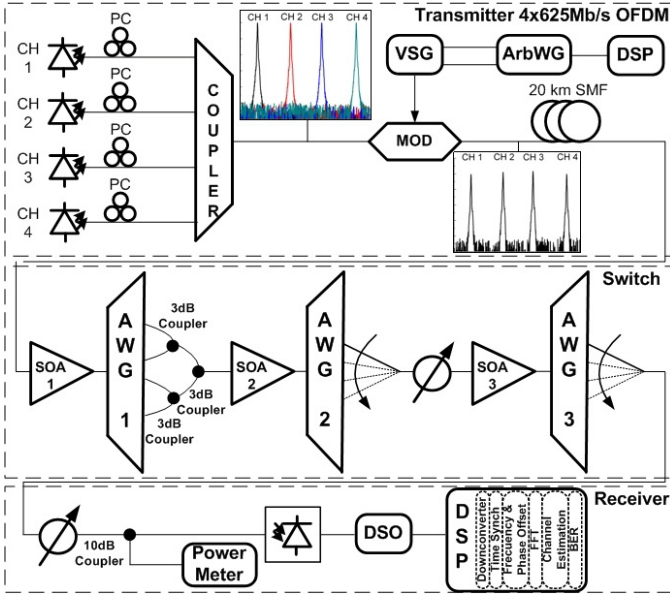


Fig. 4. Experimental setup. The insets show the optical spectra of the generated channels after being passively combined and also after modulation. PC: polarization controller, VSG: vector signal generator, ArbWG: arbitrary wave generator, DSP: digital signal processing, MOD: optical modulator, SOA: semiconductor optical amplifier, AWG: arrayed wave-guide, 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 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 SOA_1 . The output of SOA_1 was connected to AWG_1 . 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 SOA_2 and AWG_2 , and then the third stage, consisting of SOA_3 and AWG_3 . 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 SOA_3 . 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 in 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.

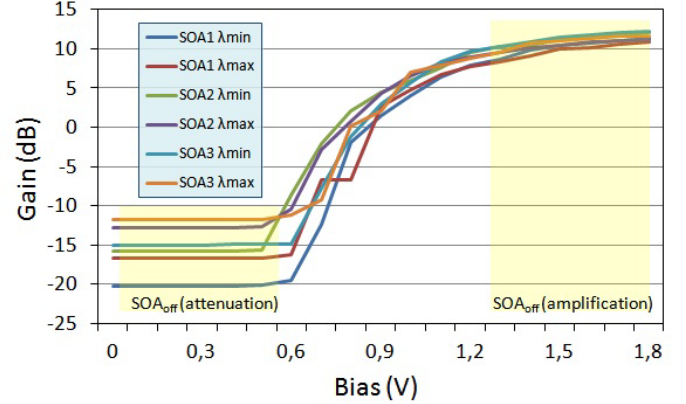


Fig. 5. Characterization of the SOAs employed in the experiment, for two different wavelengths ($\lambda_{min}=1546.8$ nm, $\lambda_{max}=1555.7$ nm). The SOAs in the optical switch are operated either in the attenuation range ($SOA_{off} \rightarrow$ Bias=0V) or the amplification range ($SOA_{on} \rightarrow$ 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 (SOA_3) 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 shows the BER performance of all the channels. As it can be observed, the back-to-back (b2b) performance is only slightly degraded (<0.5 dB) when the channel is switched to the desired output in the best (OFF) and worst case (ON) scenarios. 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.

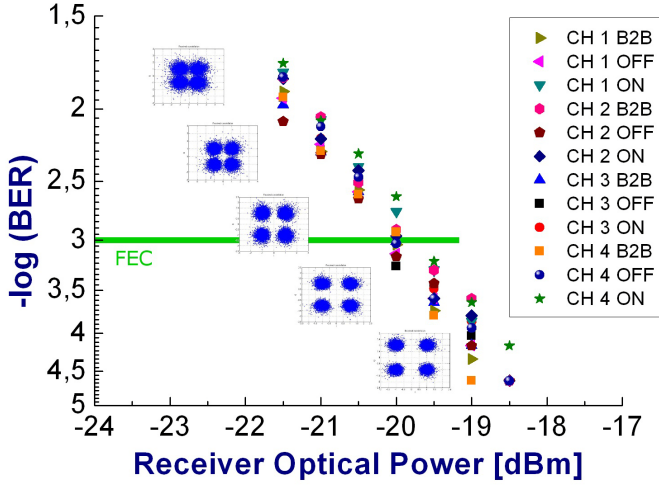


Fig. 6. BER performance of the system. The insets show the constellation of CH1 at the receiver side in the worst case scenario (rest of the channels ON). B2B: back-to-back, OFF: the other channels are set OFF by setting all SOA_{3S} OFF. ON: the other channels are set ON by setting all SOA_{3S} ON. 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 amplified spontaneous emission (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.

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.

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