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Performance analysis of 3G-UMTS WDM-RoF links

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In this paper, we analyze the impact of using directly modulated lasers and low cost optical amplifiers to propagate 3G-UMTS radio signals over fiber links. First, we perform a simulation study to identify the main impairments in such systems, and then complement the work with laboratory experiments in order to confirm the results and optimize our low cost radio over fiber system.

Keywords: radio over fiber (RoF), passive optical networks (PON), wavelength division multiplexing (WDM), UMTS, SOA.

1. Introduction

The continuous evolution of telecommunications in the last few decades has been followed by the increase of user's needs for new applications. The growth of the number of users is also related to the enormous success that the Internet brought about together with a new set of technologies that forced research for the next generations.

Passive optical networks (PON) are presented as a promising technology for the implementation of optical access networks allowing data rate transmission in the Gbit/s range for each user with low cost [1]. Some architectures and methods have been demonstrated such as time division multiplexing (TDM) and wavelength division multiplexing (WDM) providing compatibility with the existing protocols such as Ethernet and supporting asynchronous transfer mode (ATM). The basic concept of WDM technology is the capability of simultaneously transmitting information in multiple wavelengths on a single fiber, supplying a practical solution to the problem of the optic–electronic–optic transition caused by commuting along the optical network. Thus a solution that considers a total optical network to link the operator directly to the customer only over simple fiber can bring some interesting advantages.

The use of optical fiber links to distribute RF signals from a central location to remote antenna units (RAUs) is the basis of radio over fiber (RoF) technology. In communication systems, RF signal processing functions such as frequency upconversion, carrier modulation, and multiplexing are performed at the BS, and immediately fed into the antenna [2]. Thus, RAUs are significantly simplified, as they only need to perform optoelectronic conversion and amplification functions [3].

Considering all the potential of RoF as a solution for many of the actual network limitations, it can only be a reality if it is proven to be possible to implement in a cost effective way. In Figure 1, a possible setup is presented where one or more services will share the same trunk fiber and can or cannot share one of the arms of the PON, depending on the needs of the location/consumer. The losses of the PON splitting ratio may need to be compensated by a booster amplifier located at the central office.

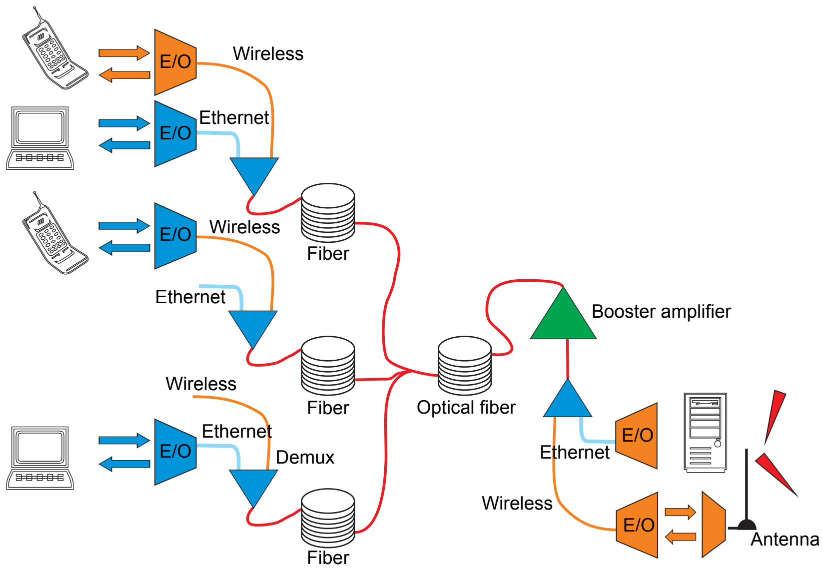

Fig. 1. Block diagram of a possible scenario.

The presence of several signals can limit the propagation of RF signals as well as make detection more difficult. It is intended, in this work, to optimize the network performance and propagation of 3G-UMTS multi-wavelength signals, using low cost optical sources and amplifiers through long-haul transmission links.

2. Simulation work

The software used in the simulation of a 3G-UMTS RoF system is the OSIP, which has been developed at the University of Aveiro. This simulator runs over the software Matlab. Figure 2 presents the radio signal generation process, considering the physical layer and modulation of the UMTS standard.

First, the information passes through a spreading operation, where the signal bandwidth is increased. This process can also be called channelization and consists in assigning a Walsh–Hadamard code for each connection, whose length can vary from 8 to 256 chips/bit, depending on the number of accesses required. The lack of synchronism and the vulnerability to multi-path are also overcome by using Gold codes in the scrambling process. The use of these codes is explained by their good autocorrelation properties that give the receiver the ability to synchronize users.

Both channelization and scrambling codes are important and used in the uplink and downlink sections with different purposes. In the uplink section channelization codes are used to separate channels of the same terminal equipment and the scrambling codes are used to separate terminal equipment. At downlink section, channelization codes are used to separate connections from users in the same cell and the scrambling codes to separate different cells. After all this processing, the information pulses are formatted by a root raised cosine (RRC) filter [4] in order to minimize the ISI and QPSK modulated.

The scheme in Fig. 2 represents two connections that correspond to two different generation processes, which are joined together at the end, corresponding to the transmission of two UMTS users. This process can be replicated. In the setups tested we analyzed the performance for 1, 8 and 16 users.

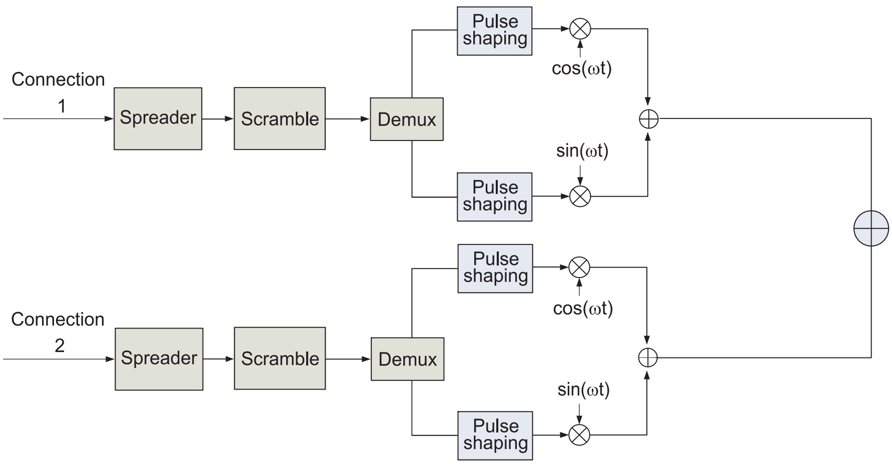

Fig. 2. UMTS signal generation.

The setup being simulated is illustrated in Fig. 3 and consists of sending an UMTS signal, followed by a duplexer, allowing uplink and downlink communications. Before modulating the laser, the signal passes through a filter and a low noise amplifier (LNA) to reduce the interference and reduce the noise factor when amplified. After this stage, the signal is used to directly modulate a laser and then propagated along variable lengths of fiber. The signal is afterwards reconverted into electrical domain and goes through a final stage, where it is driven and amplified to elevate the power level, and finally filtered before being retransmitted.

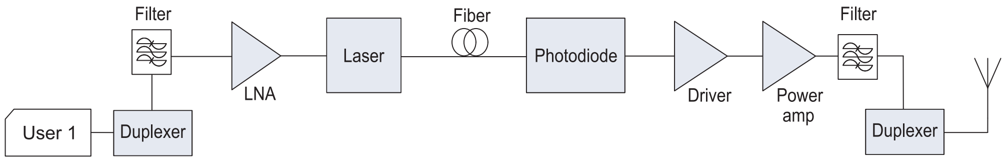

Fig. 3. Simulation setup.

The main simulation conditions of the system considered in Fig. 3 are the following:

1. When 16 connections are used:
   – Number of bits for each connection = 64 (1024 chips),
   – Bit rate 240 kbps → SF = 16;
2. When 8 connections are used:
   – Number of bits for each connection = 64 (512 chips),
   – Bit rate 480 kbps → SF = 8;
3. Samples/bit = 131072;
4. Laser average power = 1 mW; I_{bias} = 70 mA; I_{peak} = 10 mA;
5. Pulse shaping at emitter
   – Root raised cosine with $\alpha = 0.22$;
6. Receiver filtering
   – Root raised cosine with $\alpha = 0.22$;
7. Fiber model:
   – Dispersion coefficient, D = 17 ps/(km·nm),
   – Attenuation = 0.2 dB/km;
8. SNR = 15 dB;
9. f_o = 2167.5 MHz (UMTS frequency channel 12).

Depending on the simulation purposes, some of these properties may be changed, but only when is described. The value of SNR refers to the ratio between the signal power and the power of the white Gaussian noise added at the receiver. The UMTS signal transmitted corresponds to the 12-th channel of the downlink band, centered in 2.1675 GHz.

2.1. Evaluation metrics

The purpose of the simulations is to study the effects of transmitting multiple users and analyze the impact of several parameters related to laser operation, like chirp, linewidth and power level. The performance metric is the error vector magnitude (EVM) of the signal received [5].

A signal modulated in phase and amplitude can be written as

$$x(t) = I\sin(wt) + Q\cos(wt) \tag{1}$$

Thus, the EVM can be defined as in the following equation, or alternatively through the symbol constellation in Fig. 4

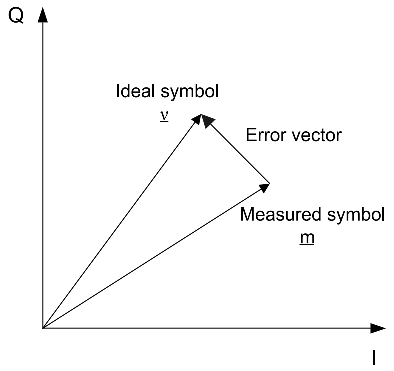

Fig. 4. Error vector magnitude (EVM).

$$\mathrm{EVM} = \frac{\sqrt{\frac{1}{N}\sum_{j=1}^{N}\left[(I_j-\tilde{I}_j)^2+(Q_j-\tilde{Q}_j)^2\right]}}{\left|\underline{v}_{\max}\right|} \tag{2}$$

where I_j and Q_j are the I and Q components of the j-th symbol of the received signal and $\tilde{I}_j$ and $\tilde{Q}_j$ are the I and Q components of the ideal one.

According to the ETSI [5] the main requirement of a system should be to meet an EVM lower than 12%, imposed for a UMTS repeater. At the receiver the phase shifts introduced along the systems are compensated, readjusting the phase of the local carrier. Thus, we may obtain the results before and after the phase correction.

2.2. Performance using multiple connections

In this section, the performance analysis of the system when a different number of users are defined at the UMTS signal generator is discussed. The results were obtained for 1, 8 and 16 users and are summarized in Fig. 5.

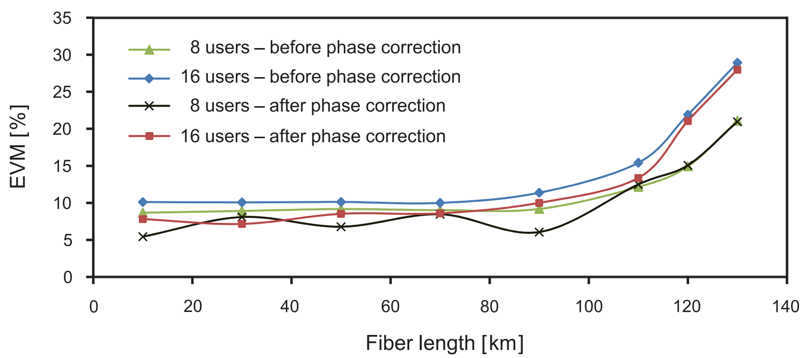

Fig. 5. Performance as a function of fiber length for 8 and 16 users.

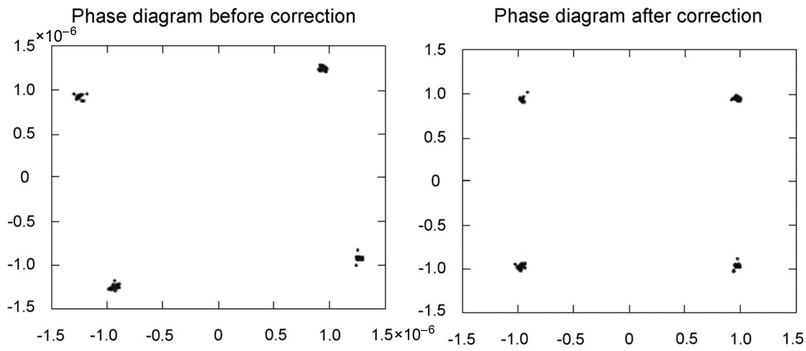

Fig. 6. UMTS constellation obtained before and after phase correction.

The results obtained for the transmission of a single user show that until 110 km of fiber length, the transmission is possible assuring the 12% limit value for EVM. The results are expressed before and after phase correction and some improvement is observed on the system performance by phase correction of the local carrier, as can be seen in Fig. 6.

When transmitting 8 and 16 users the degradation on the received signals is more evident for the second case, since for several fiber lengths the results are worst, making transmission over 100 km impossible. The phase correction done at the receiver, for 8 users, leads to an oscillating performance behavior at short distances.

2.3. Effects due to chirp

The setup used for UMTS signal transmission over fiber uses direct modulation of the laser to convert the electrical modulated signals into optical ones. This method, when compared to external modulation, has some disadvantages, as referred before, penalizing the system performance. In this section, we study the effect of laser chirp on the system performance. Chirp consists of changes in the wavelength of the emitted light caused by variations during its modulation. These frequency variations of the laser output with time are a consequence of the laser bias current variation associated with the direct modulation. The laser used in the simulations allows phase variations to be introduced in the optical signal according to:

$$\varphi(t) = \Delta\omega \int_0^t I(t)\,\mathrm{d}t \tag{3}$$

The simulation results obtained considering the setup from Fig. 3, for laser chirp of 100 MHz/mA and 200 MHz/mA are illustrated in Figs. 7 and 8, respectively. The results were obtained for both situations, considering 8 and 16 users.

From the results obtained for 100 MHz and 200 MHz of laser chirp, it can be concluded that the phase correction at the receiver is essential. Without it the EVM values obtained do not respect the ETSI [5] requirements. This is explained by

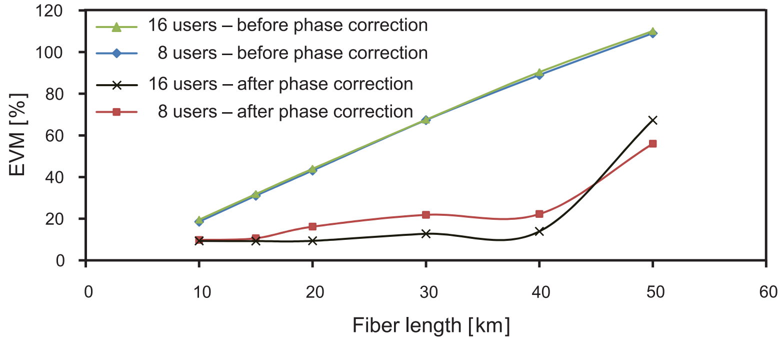

Fig. 7. Performance for laser chirp of 100 MHz/mA.

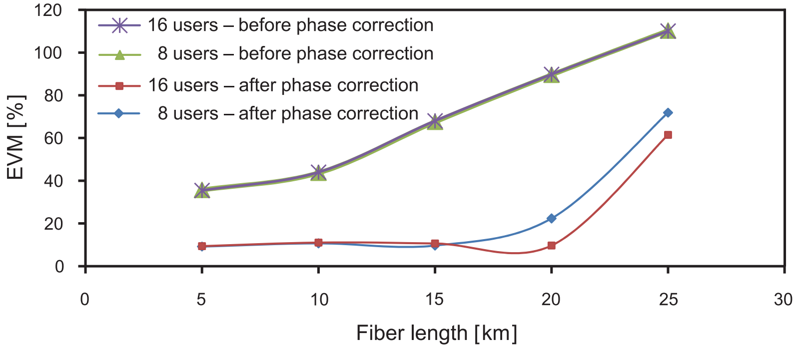

Fig. 8. Performance for laser chirp of 200 MHz/mA.

the phase shifts associated to laser chirp. When considering phase correction, the transmission within the standard value of EVM is possible and shows that the increase on chirp has a considerable effect on the maximum distance reachable by the system. For 100 MHz of laser chirp the results show a better performance when 16 users are transmitted reaching 40 km of fiber with an EVM lower than 12%, but for 8 users only 15 km were reached. Increasing the laser chirp to 200 MHz has an impact on the transmission distances enabling the transmission over 20 km for 16 users and 15 km when 8 users are transmitted.

To understand the reasons that allow the transmission with 16 connections over greater distances than with 8 connections, there is displayed in Fig. 9 the envelope of the laser current for these two situations. As can be observed, the laser envelope presents peaks of great amplitude in both situations but with smaller duration in the case of 16 connections. The increase in the number of connections has consequences in increasing the number of points in the constellation. Since the maximum current swing is always kept constant, the amplitude of transitions between two adjacent points is reduced as the number of connections increases.

This leads to a reduction of the laser current variations because the minimum current swing is now smaller. Thus, it is possible to conclude that smaller variations

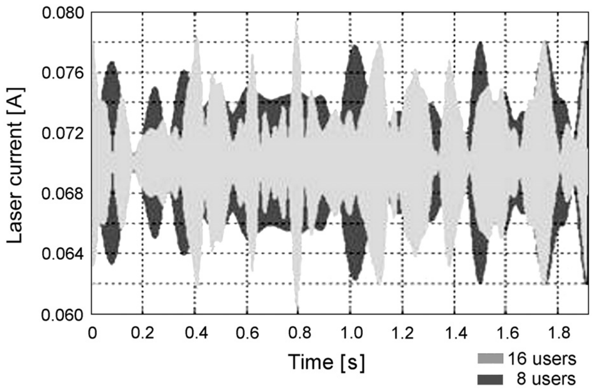

Fig. 9. Laser envelope current for 8 and 16 users.

in the laser current will cause lower phase rotations, explaining the performance increase from 8 to 16 connections.

2.4. Effects due to the laser linewidth

Ideally the laser response would correspond to a Dirac pulse in the respective desired central frequency. In fact, several factors contribute to the laser spectral broadening and this can lead to degradation in the system performance. In Figure 10, the degradation imposed for laser linewidths of 1 GHz and 2 GHz is illustrated.

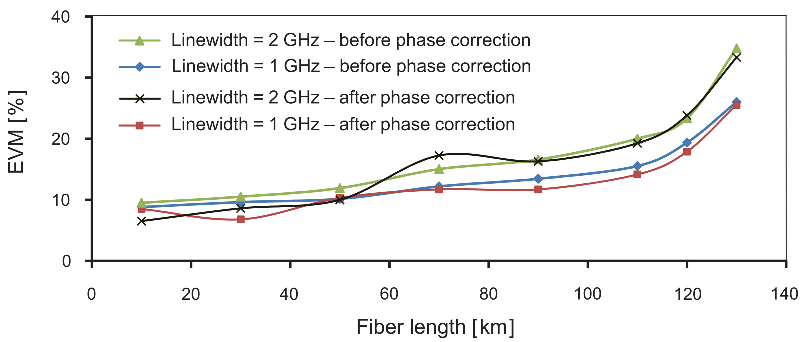

Fig. 10. Performance transmission with laser linewidth of 1 GHz and 2 GHz.

As can be seen from the results above, an increase in the laser linewidth has a significant impact on the system performance. So, for 2 GHz of the laser linewidth, transmission is only possible until 55 km of fiber, whereas for 1 GHz the system can reach 110 km of propagation distance. These results were expectable since the laser spectral broadening also causes the spectral broadening of the UMTS signal leading to intersymbol interferences that affect the signal constellation.

2.5. Performance using multiple E/O converters

When multiple optical sources are used and modulated with different signals, they must have different wavelengths so that the desired information channel can be selected trough optical filtering. This is the principle of wavelength division multiplex (WDM). However, the electrical CDMA of the UMTS signal can be used to share the medium by operating the different optical sources with the same wavelength.

In Figure 11, a setup used to simulate a multiple electro-optic (E/O) converter scenario is displayed. In this case, two channels, considering that the UMTS signals used to modulate the lasers have both 8 connections but are separated by different channelization codes, correspond to user 1 and user 2. After modulating the lasers with the same wavelength, both are connected to an optical coupler through 1 km fiber and then propagated together along various fiber distances before being converted to electrical domain by the photodiode.

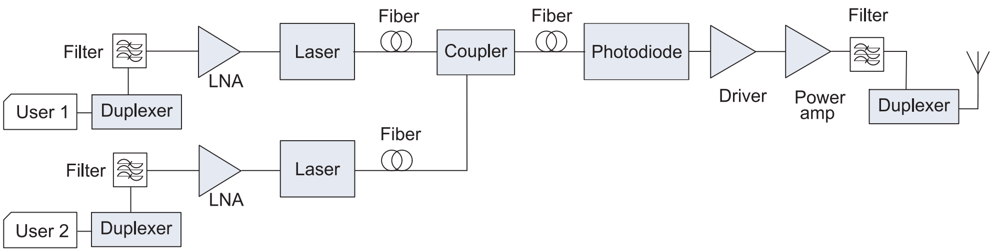

Fig. 11. Simulation setup for the transmission with two E/O converters.

We tested the transmission for a wavelength of 1550 nm in both lasers and studied the effect of progressively increasing the laser chirp. Figure 12 presents the results without laser chirp and considering 4 MHz/mA of chirp. In both cases, transmission

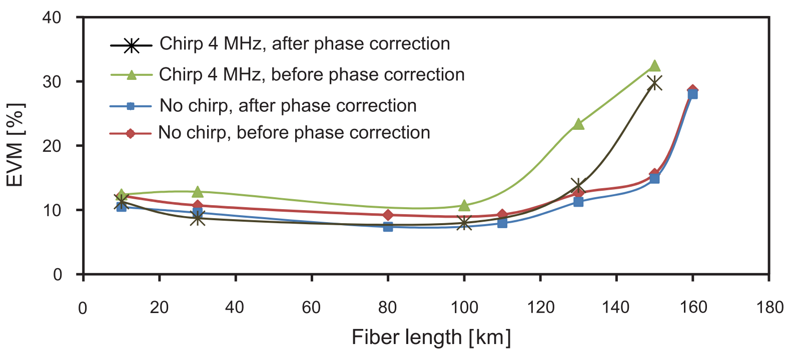

Fig. 12. Transmission of two E/O converters with and without chirp for variable fiber lengths.

within the standard EVM value of 12% is possible until almost 130 km, but when considering chirp, the phase correction mechanism is preponderant to reach the propagation distance. The increase of the laser chirp to 10 MHz/mA made transmission only possible until 100 km and for 50 MHz/mA over 60 km.

When considering laser chirp of 100 MHz/mA and 200 MHz/mA the UMTS signal transmission is compromised since these values are sufficient to reduce the propagation distance to 5 km in the first case and completely degrade transmission for 200 MHz/mA. These results were expected since each UMTS frequency slot has only 3.84 MHz of bandwidth and the chirp causes spectral broadening due to an instantaneous frequency change.

3. Experimental work

To complement the simulation work on 3G-UMTS RoF links, we created an experimental scenario to conclude about the reliability of such a system. Figures 13 and 14 illustrate the setups used. The radio frequency (RF) signals are provided through a Rohde and Schwartz vector signal generator that is used to directly modulate a laser, emitting at 1.55 μm. In the WDM scenario, the RF signal is on one channel and the AM modulated one (an amplitude modulated ECL laser) 2 nm higher. The optical signal is then pre-amplified in both cases using a SOA with an internal pump laser

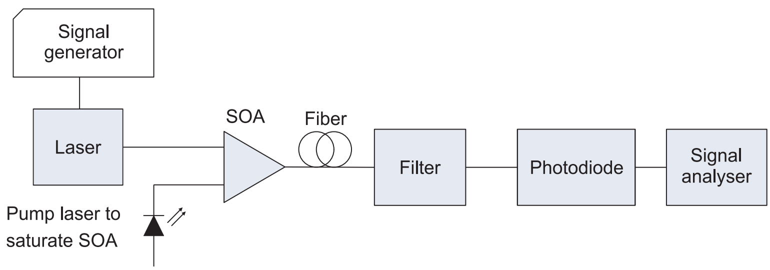

Fig. 13. Single channel setup.

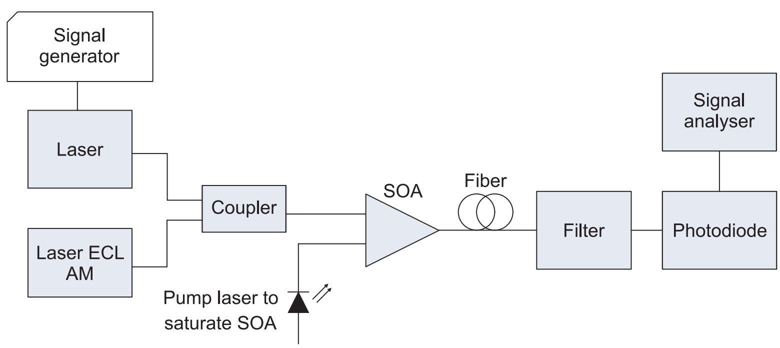

Fig. 14. WDM setup.

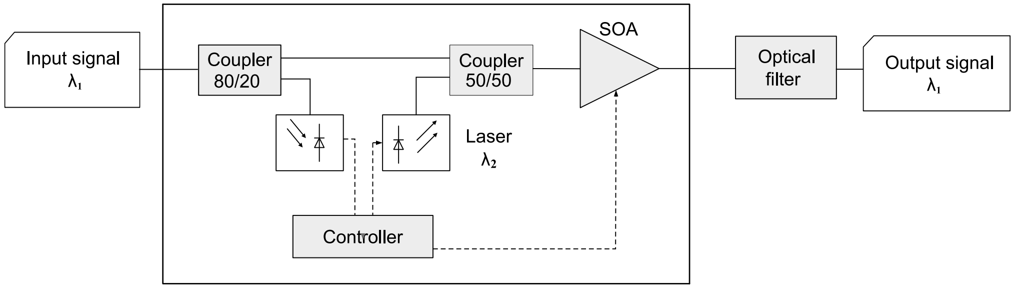

Fig. 15. The SOA setup used.

(1 nm below the RF channel) to control saturation, and transmitted over a standard single mode fiber. At the output, the RF signal channel is filtered, detected and applied to a vector signal analyzer to assess performance.

Considering the setup in Fig. 13, an SOA is used as a booster amplifier to amplify the optical channel together with a laser. The laser pump is used to saturate the SOA by varying its biasing current, providing the gain decrease. In this setup, it is also important to notice that before detecting and analyzing the RF signal it is needed to filter the 1550 nm DFB laser channel eliminating the pump laser and other spectral components originated by FWM.

The gain saturation of the SOA used is achieved with a laser pump at 1548.63 nm. The setup used is the one in Fig. 15 that considers the possible utilization of a control mechanism in order to maintain the SOA always at saturation. Anyway, this was not used and the SOA response without the pump laser and for different biasing currents of the pump was studied.

The respective gain curves for the input power of the laser, for the different schemes, are illustrated in Fig. 16.

For the different biasing currents, there is observed the SOA saturation behavior evidenced by its gain decrease and stabilization for the higher currents. Without

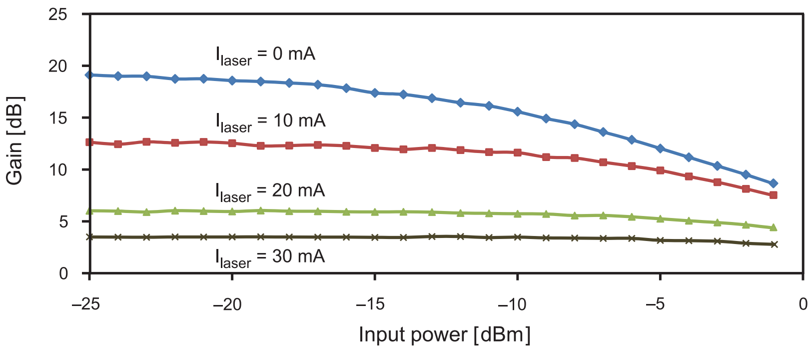

Fig. 16. SOA gain curves with the input power for different biasing currents of the pump laser.

the pump laser, the gain falls by 3 dB when the input signal reaches –11 dBm. For the other biasing currents the gain is mainly constant with the increase of the input signal power, showing that the amplifier is already in saturation.

In the setup used, the DFB laser biased with 20 mA or 30 mA presents an output power higher than 1 dBm, so the SOA will be saturated. Thus, when considering the pump laser, the SOA will be even more saturated, which effect can be confirmed by comparing the results for the two situations.

3.1. Single channel RoF system

We tested back-to-back transmission and along 20, 40 and 60 km of SMF considering SOA saturation with and without pump laser biased with a current of 30 mA. The results are summarized in Fig. 17 for the transmission of 3G-UMTS signals.

For each fiber length, there is presented the propagation with SOA at saturation with the pump laser biased with 30 mA and without pump. From this analysis it can be noticed that with the SOA in saturation, when considering transmission over 20, 40 and 60 km, the results become worst due to its internal dynamics (SPM and SGM), but in the back-to-back transmission with pump saturation leads to better results. This behavior, when the SOA is directly linked to the PIN, can be explained by the fact that when the amplifier is less saturated, phase rotations can lead to a high and quick transient peak that does not occur when the SOA is saturated with the pump. Nevertheless, the transmission of UMTS is assured over 60 km of fiber.

For the case of transmitting the RF signals for different biasing currents of the laser pump over the same fiber distance, the results obtained are displayed in Fig. 18. The best results are for the unsaturated operation (pump laser off) due to higher gain.

When biasing the pump laser with 10 mA, the results show higher degradation when compared to the other pump biasing currents. This fact can be explained by the observation of the SOA saturation curves that show a more linear behavior for

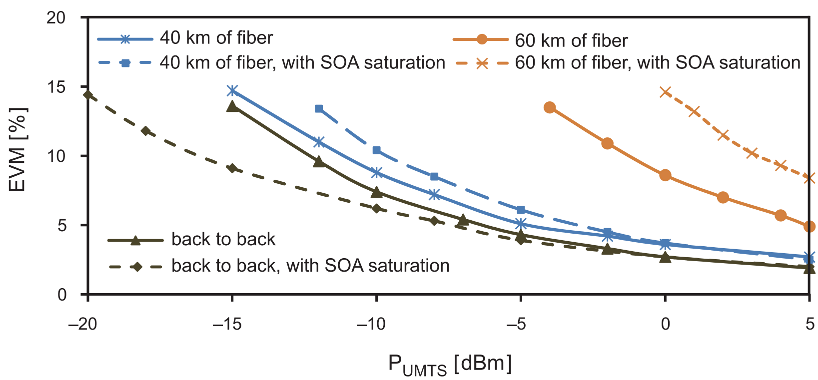

Fig. 17. EVM versus input UMTS power considering unsaturated SOA and saturated SOA with a pump laser current of 30 mA for back-to-back transmission and different fiber lengths.

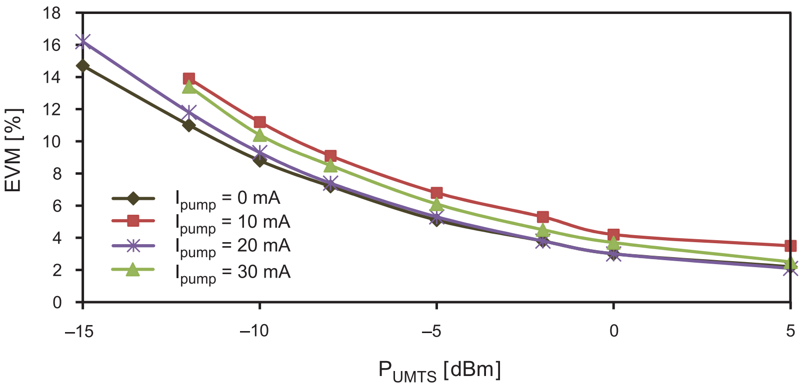

Fig. 18. EVM versus input UMTS power for SOA with different biasing currents over 40 km of fiber.

higher input powers at the SOA, in the case of 20 and 30 mA. Thus, the gain saturation can be more relevant when pump is biased with 10 mA. When comparing the results for 20 and 30 mA, they are similar, but with higher EVM values for 30 mA, due to a higher saturation, and therefore a lower gain.

In Figure 19, there are displayed the constellations obtained at the analyzer for the transmission of UMTS signals considering a power level of 0 dBm at the generator. The constellations presented differ in the propagation distance and the saturation of the SOA.

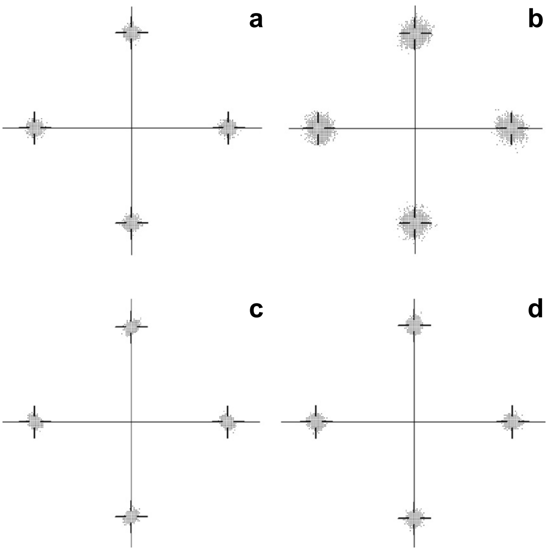

Fig. 19. Constellations of the UMTS received signals for a single channel setup: 40 km of fiber with unsaturated SOA – **a**; 40 km of fiber with SOA saturation (30 mA) – **b**; 60 km of fiber with unsaturated SOA – **c**; 60 km of fiber with SOA saturation (30 mA) – **d**.

3.2. Multi channel RoF system

In the WDM scenario described (Fig. 14), when transmitting an amplitude modulated (AM) signal together with the reference RF signals, considering the SOA saturation with the pump laser, the separation between channels will be much more relevant. The AM signal is provided as reference before by an ECL, thus a central wavelength of 1552 nm was selected in order to mitigate the FWM between channels. The AM signal has a frequency of 1 MHz and the optical signal at the output of the laser presents a mean power corresponding to the biasing chosen.

In this setup, besides SPM and SGM, there will be also XPM and XGM, caused by phase and gain changes induced by the AM signal on the RF one. To analyze the effect of the SOA nonlinearities when considering both channels, we tested the transmission with a laser pump biasing current of 20 mA, to saturate the amplifier, over different SMF distances. The results are summarized in Fig. 20.

The effects of crosstalk can be confirmed by observing the constellations of UMTS signals, obtained when varying the laser pump current of the SOA, for a fixed power of –5 dBm on the AM laser. We observe the degradation of the results due to XGM (Fig. 21). The increase of the biasing current of the pump laser has a considerable

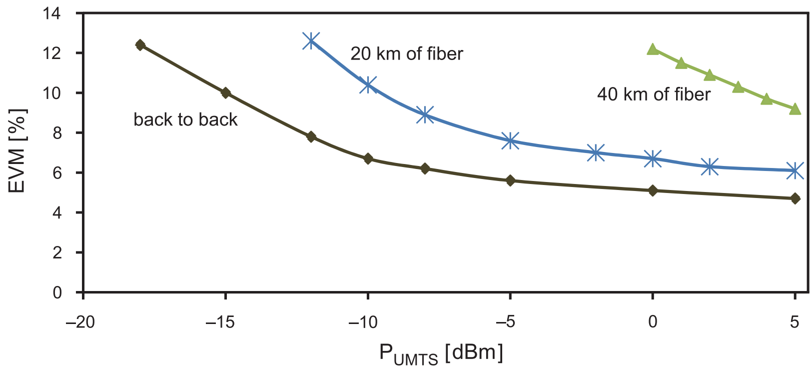

Fig. 20. EVM versus input UMTS power considering a laser pump current of 20 mA.

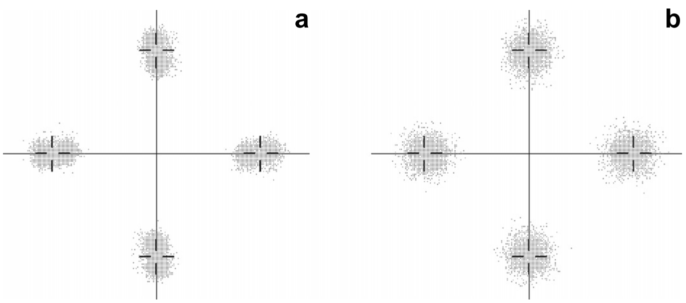

Fig. 21. Constellations of the received UMTS signal: SOA saturation with 20 mA on the laser pump – **a**, and SOA saturation with 30 mA on the laser pump – **b**.

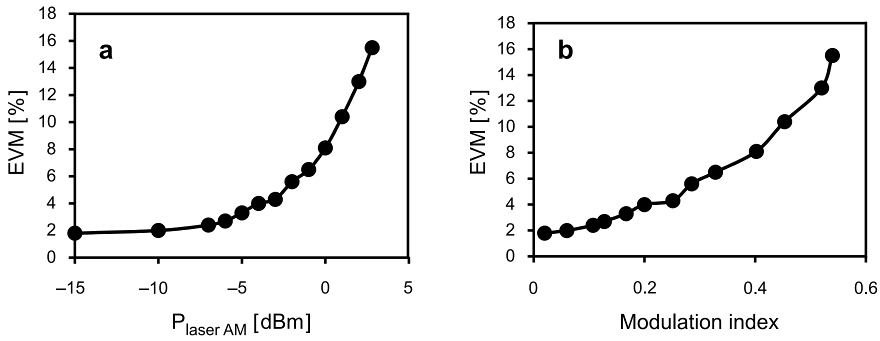

Fig. 22. System performance for the transmission of multiple channels with SOA saturation (30 mA): EVM versus optical power of the AM laser – **a**, EVM versus modulation index of the AM laser – **b**.

effect on the constellation obtained, with some symbols starting to spread, leading to higher EVM values.

In the next experiment, varying the attenuation of the AM laser output, the modulation index and mean power of this channel will decrease, resulting in an improved received RF signal, due to less significant inter-channel crosstalk and lower saturation.

With the purpose of measuring the modulation index of the AM channel, the extinction ratio of the signal was obtained by attenuating the laser power and directly connecting it to the PIN followed by an oscilloscope. Considering the PIN photodiode responsivity, the modulation index at the SOA input was determined for the same pump laser biasing.

Figure 22 presents the EVM versus the optical power of the AM laser and the EVM versus the modulation index of the AM laser for the transmission of UMTS signals, with the pump laser polarized with 30 mA.

As was expected, a decrease in the modulation index of the AM channel obtained by attenuating the output power of the laser and maintaining the same power on the pump laser to saturate the SOA, enhances the system performance. This behavior is justified by less interchannel crosstalk effects, thus the results will be less affected by the SOA non-linearity like XPM and XGM.

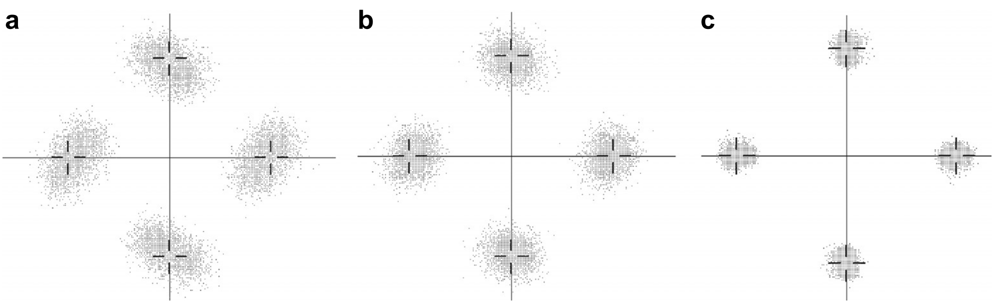

Fig. 23. Constellations of the received UMTS signal: modulation index = 0.54 – **a**, modulation index = 0.4 – **b**, and modulation index = 0.2 – **c**.

In Figure 23**a**, for 3 dBm of the AM laser corresponding to a modulation index of 0.54, besides the amplitude fluctuations, there are observed phase changes in the constellation due to the strong saturation and gain dynamics. In Figures 23**b** and 23**c**, for a modulation index of 0.4 and 0.2 respectively, the crosstalk effects are reduced and the symbols are more concentrated improving the EVM results.

4. Conclusions

The simulation results, when compared to the practical implementation, showed a limitation in the EVM values obtained, even when propagating through small trunks of fiber. It can be concluded that the fact of the EVM being higher than 7% or 8% in all the tests may be related to difficulties to adapt the root raised cosine filter at the UMTS generator and receiver, leading to a stabilization around those values for several fiber distances instead of a continuous evolution as was obtained in practice. Nevertheless, the simulation work studied the propagation of multiple users in the WCDMA-3GPP layer and the effect of directly modulating a laser for the transmission of such signals when varying chirp or linewidth.

The transmission of a single channel RF modulated laser, proved the reliability of RoF systems to overcome the RF spectrum limitations and assure propagation coverage in difficult environments provided by distributed antenna systems. The WDM-RoF system implemented showed that the transmission of multi-wavelength signals is possible, sharing the same trunk of fiber, compensating the losses of the splitting ratio with a booster amplifier located at the central office.

Testing the transmission of a channel consisting of an AM signal that can be Ethernet or other, together with RF modulated one, demonstrated that optical fiber can be used providing high bandwidths on each channel, increasing the users bandwidth and data-rate in a real scenario.

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