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Radio over Fiber (RoF):
A comparison of low-cost systems

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Abstract: In order to assess the potential of low-cost radio-over-fiber (RoF) solutions, in this paper we make a comparison of three full-duplex RoF systems. These systems are low-cost solutions that use remote modulation, with a single centralized light source used at the central station to generate a downlink wavelength that is reused at the remote location for upstream transmission. By avoiding the need for an additional light source at each remote location the cost of the solution is significantly reduced. The three systems evaluated in this paper differ by the type of optical modulation used for downlink and uplink. The first is an IM-IM system using intensity-modulation (IM) for the downlink and uplink direction. The second scheme, PM-IM, differs from the first by using phase-modulation (PM) for downlink. Finally, the third system, PM-PM, uses phase modulation for downlink and uplink.

1. INTRODUCTION

By combining the enormous capacity and low transmission loss of optical fiber networks with the ubiquity and mobility of wireless networks, radio-over-fiber (RoF) transmission techniques form a powerful platform for the support of emerging applications and services [1]. By allowing the centralization of complex signal processing, they enable the implementation of simple, compact, and low-cost remote base stations. Considering the downlink as an example, in a RoF system the radio signals are processed and modulated at the Central Station (CS) and are then delivered to the Remote Unit (RU) using an optical fiber. The RU has the sole responsibility of demodulating and transmitting these signals wirelessly. All complex signal processing is done at the CS.

In order to simplify the RUs and reduce the associated costs, RoF architectures with a single optical source have been proposed [2]. In these low-cost solutions the optical carrier is generated in the CS and modulated with the electrical Radio-Frequency (RF) signal for downlink transmission. In the RU the optical carrier is reused to modulate the uplink signal.

Both the downlink and the uplink can use different types of optical modulation (e.g. Intensity Modulation (IM) and Phase Modulation (PM)) as presented in [2-4]. In this paper we make a comparison between three different low-cost systems with different combinations of optical modulations, namely IM in both downlink and uplink, PM in downlink and IM in uplink, and PM in downlink and uplink.

For the comparison we consider two figures of merit: the Error-Vector-Magnitude (EVM) and the received constellations. We simulated the three RoF systems described using the VPIphotonics™ simulator.

The rest of this paper is organized as follows. In section 2 we describe and quantify the general parameters of the systems analyzed. The IM-IM, PM-IM and PM-PM RoF systems are presented and evaluated in sections 3, 4, and 5, respectively. Finally, section 6 concludes this paper with a discussion on the three schemes compared.

2. GENERAL PARAMETERS

The three systems use the same type of RF signals. As input 16-QAM is used for downlink and QPSK modulation for uplink. The main features of these signals are presented in Table 1.

Downlink RF signal	Modulation	16-QAM
	Bit Rate	200Mb/s
	Radio Frequency	5.9GHz
	Bandwidth	60MHz
Uplink RF signal	Modulation	QPSK
	Bit Rate	100Mb/s
	Radio Frequency	6GHz
	Bandwidth	60 MHz

Table 1 - RF signals parameters.

As the main purpose is to obtain a low-cost system, we use only one Continuous Wave (CW) Distributed Feedback Laser (DFB) at the source. The optical fiber used in all systems is a Dispersion Shifted Fiber (DSF). This type of fiber is typical for broadband wireless access [2]. Finally, the photodetection is made by means of a PIN photodiode. The main characteristics of each component are presented in Table 2.

Laser	Type	DFB
	Average Power	1mW
	Emission Frequency	192.3THz (1552.64nm)
	Linewidth	10MHz
Optical Fiber	Type	SMF-DSF
	Reference Frequency	192.3THz (1552.64nm)
	Attenuation	0.2dB/km
	Dispersion	0,787ps/(nm km)
	Length	25km
Photodiode	Type	PIN
	Responsivity	1A/W
	Dark Current	0A
	Thermal Noise	$10pA/Hz^{1/2}$

Table 2 - Optical components parameters.

The main difference between the three systems is the optical modulation used for downlink and uplink. When IM is used the optical modulator is an ElectroAbsorption Modulator (EAM). For PM the optical modulator used is an ideal phase modulator. In the reception, when the modulation is IM, we use a single photodiode. In the case of PM, we use a 25ps Delay Interferometer (DI) followed by a balanced receiver with two photodiodes.

3. IM-IM SYSTEM

The first system analyzed is presented in Figure 1, where IM is used in both directions. The optical carrier is modulated with an EAM driven by a 16-QAM signal for downlink transmission in the fiber. In the RU the received signal is split and half of the optical signal power is converted to electrical by a photodiode. For the uplink, the second output of the splitter is remodulated by another EAM driven by a QPSK signal. The uplink transmission and reception of the optical signal is identical to the downlink.

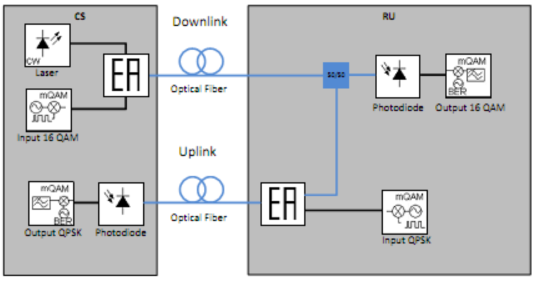

Figure 1 - IM-IM system.

3.1 Results: Downlink transmission

For this system, the EVM as a function of the Modulation Index (MI) is shown in Figure 2.

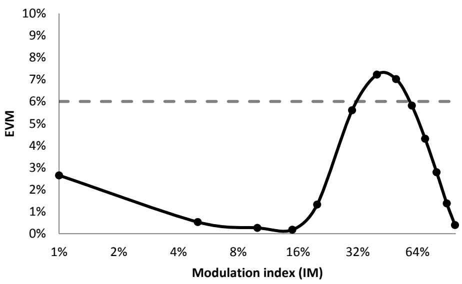

Figure 2 - EVM as a function of the MI in downlink for the IM-IM system.

According to the WiMAX standard [5], the EVM should be of 6% for 16-QAM and of 12% for QPSK to guarantee good performance. As we are assuming this type of broadband signals, we use these values as reference in all figures. By analyzing Figure 2 we can conclude that the MI value that resulted in the best EVM (0.17%) is 15%. To guarantee an EVM below the threshold of 6%, the MI has to be outside the range 30%-60%.

In Figure 3 and Figure 4 we present the constellation and 16-QAM signal spectrum in the receiver for the best MI value, respectively. As expected from the EVM value obtained, we can observe that the symbols appear very well defined in the constellation and that the SNR has an acceptable value.

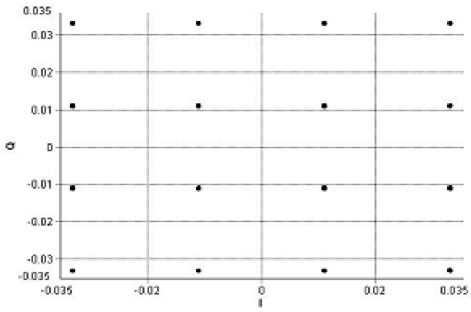

Figure 3 - Constellation in downlink for an MI of 15%.

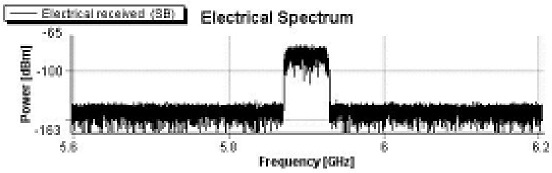

Figure 4 - Signal spectrum in downlink for an MI of 15%.

For the worst value of MI (40%) the constellation appears noisy and the SNR worsens, as we can see in Figure 5 and Figure 6, respectively.

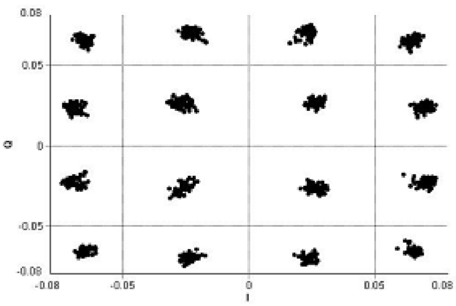

Figure 5 - Constellation in downlink for an MI of 40%.

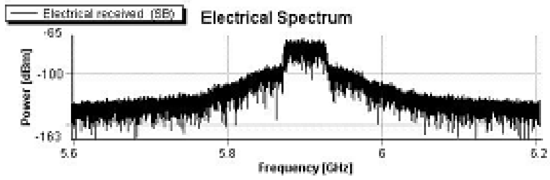

Figure 6 - Signal spectrum in downlink receiver for MI of 40%.

In conclusion, by choosing an adequate MI we can achieve very good performance in downlink.

3.2 Results: Uplink transmission

As in the downlink case, we also present the EVM as a function of the MI. Figure 7 shows the EVM as a function of the MI in uplink with a fixed downlink MI of 15%. In this case, the RF signal is modulated in QPSK, increasing the limit of EVM to 12%, according to the standard.

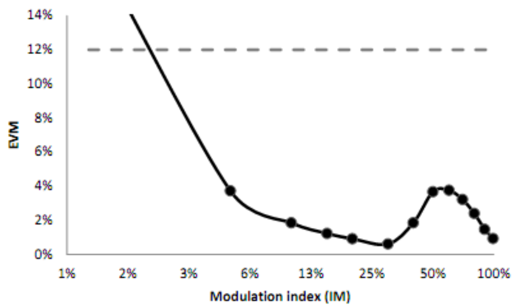

Figure 7 - EVM as a function of the MI in uplink with a fixed downlink MI of 15%.

In the uplink the choice of the MI is less restrictive than in the downlink, due to the distance between symbols in the QPSK constellation be higher than in 16-QAM. The MI which results in lower EVM is 30% as can be seen in Figure 7.

The reception of the uplink signal is shown in Figure 8. By analyzing the figure, we can see also the downlink signal, because the uplink receiver demodulates both IM signals.

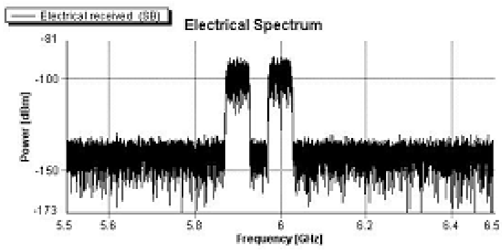

Figure 8 - Signal spectrum in uplink of IM-IM system.

The reception of these two channels causes interference, which can be minimized by limiting the power of the downlink channel. This power can be limited by adjusting the downlink MI.

It is therefore important to study how the EVM varies in uplink as a function of the MI for downlink. In Figure 9 we can observe this variation, by fixing the uplink MI to30%.

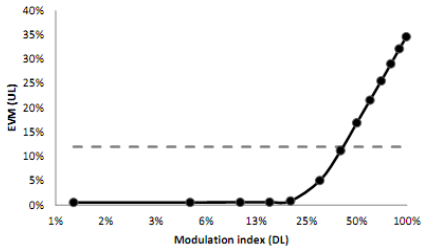

Figure 9 - EVM in uplink as a function of the MI of downlink.

From this figure, we can conclude that in an IM-IM system, the downlink MI should be limited to 30%, to allow bidirectional communication.

4. PM-IM SYSTEM

In the PM-IM system, presented in Figure 10, PM is used for the downlink direction. This system was discussed in [2,6]. In the RU the received downlink signal is input to a 25ps delay interferometer (DI) to demodulate the PM signal. The null frequency of the constructive port of the DI is detuned by 5.9 GHz from the signal wavelength to eliminate one of first-order sidebands, in order to increase the received power by removing beating effects. The output of the DI is detected by a balanced receiver to increase the Signal to Noise Ratio (SNR) [2].

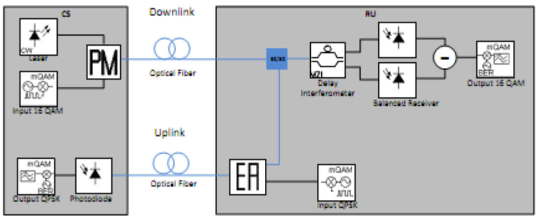

Figure 10 - Architecture of the PM-IM system.

4.1 Results: Downlink transmission

For the PM-IM system, the EVM as a function of the normalized PM index is shown in Figure 11 for the downlink. The normalized PM index is the ratio between the PM index, in degrees, and the phase between adjacent symbols, which for 16-QAM is 22.5º. We can see that the minimum EVM value is 1.28% for an MI of 31.1%. The PM index must be inside the range 4.4%-70%.

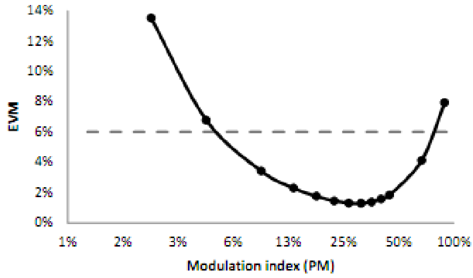

Figure 11 - EVM as a function of the MI in downlink of the PM-IM system.

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The received downlink signal constellation of the PM-IM system for the modulation index value that resulted in the best EVM is shown in Figure 12. The symbols appear very well defined in the constellation. However, note that this constellation is rotated due to the 25ps delay introduced in the DI. This does not affect the EVM because the receiver uses amplitude and phase correction.

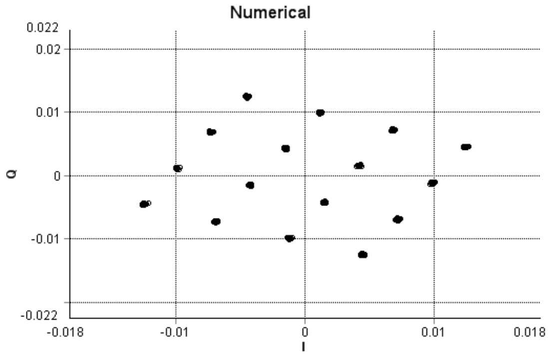

Figure 12 - Received constellation in downlink of the PM-IM system.

4.2 Results: Uplink transmission

The uplink of this system is the same as the one from the IM-IM system. Figure 13 shows the EVM in uplink as a function of the MI in downlink, for a fixed uplink MI of 30%.

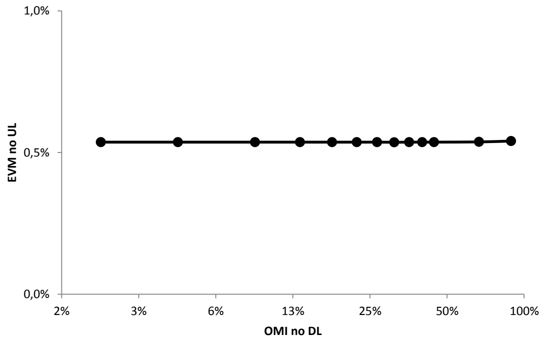

Figure 13 - EVM in uplink as a function of the MI in downlink with a fixed uplink MI of 30%.

By analyzing the figure we can conclude that the downlink MI has no influence on the uplink transmission. Contrary to the IM-IM low-cost solutions, due to the constant intensity of the PM signal the modulation index of the downlink signal is not sacrificed and the power budget of the uplink is improved. This fact is the main advantage of a PM-IM solution when compared to IM-IM.

The main limitation of this system is related to the existence of the phase modulation to intensity modulation (PM-to-IM) conversion effect caused by chromatic dispersion of the optical fiber. To assess this problem, in Figure 14 we present the uplink signal at the receiver with the PM downlink signal.

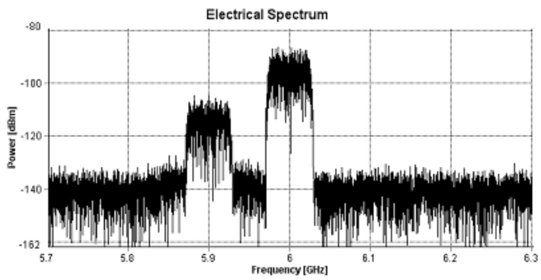

Figure 14 - PM-to-IM effect on uplink receiver.

The PM-to-IM effect causes no major constraint because the power of the signal generated by the PM-to-IM effect is two orders of magnitude lower than the power of the uplink signal.

5. PM-PM SYSTEM

Finally, we present a system using PM for both downlink and uplink. The architecture of the PM-PM system is presented in Figure 15.

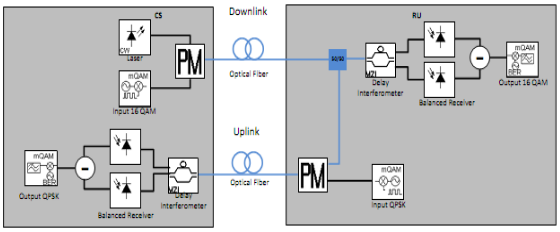

Figure 15 - Architecture of a PM-PM system.

As the downlink of the PM-PM system is equivalent to the downlink of the PM-IM system, in this section we focus only in the uplink direction.

5.1 Results: Uplink transmission

The EVM as a function of the normalized PM index is shown in Figure 16.

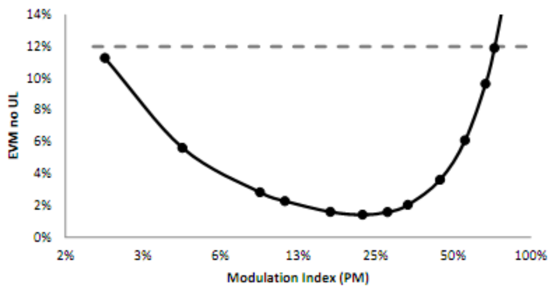

Figure 16 - EVM as a function of the MI for uplink in the PM-PM system.

The EVM is acceptable for all values of the modulation index from 2.2% to 72.2%. As we can see in the figure, the best EVM value obtained is 1.43% for a MI of 22.2%.

Another important issue is the influence of the downlink MI for the uplink reception. Although the downlink has constant intensity, the utilization of the same type of modulation causes interference in the uplink receiver, because the DI of the uplink demodulates both the downlink and the uplink signals. The EVM for uplink as a function of the MI for downlink, with a fixed uplink MI of 22.2%, is shown in Figure 17.

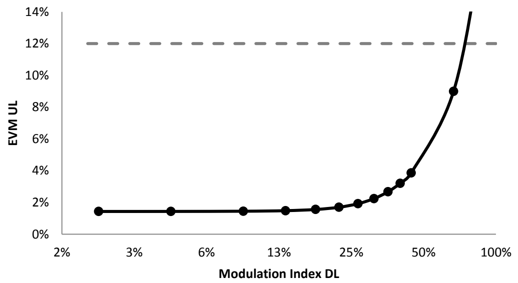

Figure 17 - EVM in uplink as a function of the MI for downlink in the PM-PM system.

By analyzing Figure 17 it is possible to conclude that the EVM for uplink is indeed influenced by the downlink MI. The best EVM values are obtained when the downlink uses low values of MI. By taking into account both constraints, we conclude that the downlink MI should be restricted to the range 4.4%-70%.

Figure 18 shows the uplink signal at the receiver using the best values of the MI, 31.1% for downlink and 22.2% for uplink.

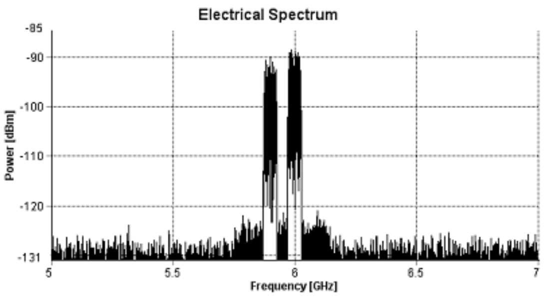

Figure 18 – Signal spectrum in uplink of PM-PM system.

In the figure we can see the two channels present in the uplink receiver. This is due to the fact that the PM receiver in uplink also demodulates the PM downlink signal. This situation is similar to the IM-IM case.

6. DISCUSSION

To conclude the paper we present a brief discussion on the results obtained.

Considering the IM-IM system, it is possible to achieve good performance if the MI is outside the range 30%-60%. However, as the uplink is also influenced by the downlink MI, and therefore, the downlink MI is limited to 30% to allow bidirectional communication. The uplink MI is not limited for values above 2.2%.

For the PM-IM system the downlink MI is not limited by the uplink performance, due the constant intensity of the PM signal. The limitation of MI for both directions is thus independent. Being less restriction in the choice of the MI is an important advantage of this system.

The PM-PM system presents similar problems of the IM-IM system, as the PM receiver of the uplink is able to demodulate the PM downlink signal. The downlink MI thus limits the uplink performance.

As a final note, it is important to emphasize that for applications where a high modulation index is not required, the solution with IM is a preferable choice due the simplicity of the receiver.

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