Digitised Radio Techniques for Fibre-Wireless Applications

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ABSTRACT
In this paper we present a comprehensive analysis and a performance assessment on the transmission of digitised RF signals over optical fibre (DRoF). Specifically, a study of the impact of the ADC/DAC quantization, jitter noise and the signal attenuation caused by the sub-sampling technique and DAC frequency roll-off are addressed by means of simulation, considering the transmission of RF signals conveying QAM symbols. Additionally, an experimental evaluation of DRoF links using vertical-cavity surface-emitting lasers (VCSEL) for different optical fibre attenuation levels is also conducted. Finally, a new paradigm of DRoF systems based on well-known sigma-delta modulators (SDM) is also presented. Results show that it is possible to digitally transmit signals through a digital optical-based network and to distribute them wirelessly at the receiver side without the need for local oscillators (LO) and/or frequency up-converters. Results also show that the new sigma-delta-over-fibre concept performs similarly to conventional DRoF schemes, whilst being more competitive for either upgrading installed systems as well as for new deployments.
Keywords: Digitised Radio-over-Fibre, sigma-delta modulator, VCSEL, quantisation noise.

1. INTRODUCTION

Radio-over-Fibre (RoF) techniques are considered today as very promising to facilitate the backhauling of a large number of remote antennas, enabling the shifting of the hardware complexity from the base station (BS) to the control station (CS) [1]. RoF consists in transporting the radio signals over optical fibre by means of an optical carrier between a remote site/BS and the head-end/CS node of the cellular network, in a completely transparent, frequency/protocol agnostic manner [2].

The main performance-limiting factor in analogue RoF (ARoF) systems consists of its nonlinear behaviour mainly due to electrical-to-optical converters (EOC) devices that cause the emergence of intermodulation distortion (IMD) and, consequently, also affects the dynamic range of the analogue link [3][4]. To overcome them, researchers have been proposing the transmission of digitised RF signals over fibre that merge both optical and electronic digitisation worlds as an alternative [5].

Although DRoF schemes are an interesting alternative to their analogue counterparts, the fact that the remote site requires the employment of a high bandwidth DAC may be a disadvantage, and therefore the existence of a viable alternative would be desirable. Here we also propose a novel solution for the implementation of future DRoF systems based on the usage of a bandpass (BP) sigma-delta modulator (SDM) at the transmitter side, working as a 1-bit ADC, which avoids the need of a DAC at the receiver side [6]. Moreover, we show, according to the best of our knowledge, the world's first digitised RoF solution avoiding the employment of a DAC at the receiver, and capable of achieving RF carrier signals in the GHz region by extracting high frequency signal replicas that arise due to properties of the SD based digital transmission over fibre.

With respect to DRoF, we present experimental results that address the impact of quantisation and jitter noises on the performance of the system, as well as the impact of the attenuation caused by the frequency roll-off of the DAC and by the sub-sampling technique. Regarding the proposed SDM concept, a performance analysis is carried out considering a system based on VCSEL and a discussion regarding its performance relative to conventional DRoF systems is presented.

This paper is organized as follows: in section 2 we present and evaluate the conventional DRoF system; in section 3 we present and evaluate the new SD-over-fibre paradigm; in section 4 we present a comparative analysis of the system concepts evaluated; and finally section 5 draws the conclusions.

2. THE DIGITISED RADIO-OVER-FIBRE SYSTEM

DRoF transport schemes that merge both optical and electronic digitisation worlds are being studied and pointed as viable alternative solutions to ARoF systems [5]. In Figure 1 a typical DRoF scheme is depicted. DRoF requires the usage of high bandwidth ADC converters at the transmitter side and DAC converters at the receiver side. Contrary to analogue systems, by employing DRoF the IMD is avoided and the dynamic range of the system remains constant and irrespective of the optical fibre length, provided that the received signal amplitude is above the sensitivity of the link [7]. Moreover sub-sampling may be used in DRoF schemes to lower the sampling rate requirements since most common wireless standards (e.g., WiMAX, WiFi, 3G, 4G) have small fractional bandwidths relative to their carrier frequencies [4].

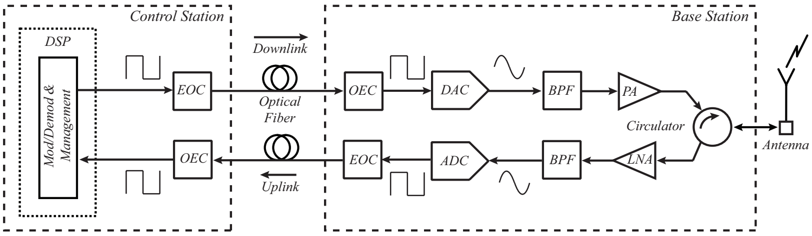

Figure 1: Diagram of the digitised radio-over-fibre architecture.

2.1 Experimental setup and results

The schematic of the experimental setup used is illustrated in Figure 2. The QAM mod/demod, LO and ADC/DAC operations are implemented in Matlab. The stream of bits is then uploaded into the pattern generator (serial BERT Agilent N4906B) and directly modulates a 1550 nm VCSEL diode. After passing through an optical attenuator, the digital sequence is converted into the electrical domain by means of a photodiode (Agilent 81495A reference receiver) and sampled by the pattern detector (serial BERT). Then, the sequence is uploaded into Matlab and performance evaluation is performed.

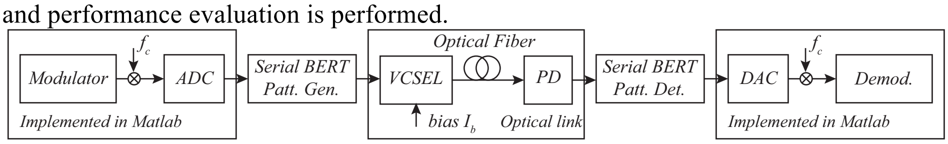

Figure 2: DRoF experimental setup schematic.

The RF signal is considered to be a 16-QAM, centred at 2.475 GHz, with a symbol rate of 5 MS/s and a raised cosine roll-off factor of 0.25. The VCSEL was biased at 6.25 mA to ensure the necessary bandwidth and the extinction ratio was set to 10 dB. Figure 3 depicts the spectra of the output of the DAC considering a sampling frequency, f_s, of 125 MHz and different quantization bits, N_b. As it can be seen, the noise power decreases log-linearly at a rate of (theoretically) 6.02 dB with N_b down to the level where the jitter noise starts to dominate. It can also be seen the attenuation caused by the frequency roll-off of the DAC.

In order to evaluate the performance of the DRoF system, we have considered the modulation error rate (MER) metric. In Figure 4 the MER is depicted as a function of the ADC sampling frequency (using N_b = 7 bits) for the first replica at 25 MHz and fundamental signal at 2.475 GHz and for two ADC jitter noise levels. As expected, the performance decreases with the jitter noise. Additionally, the MER of the signal at 2.475 GHz is severely affected for low ADC sampling frequencies due to the frequency roll-off effect of the DAC (see *Figure 3*). For that same reason, this effect is almost negligible for the first replica signal.

We now consider a specific case where the ADC/DAC has N_b = 6, t_j = 0.8 ps and f_s = 750 MHz. Figure 5 shows both MER and BER as a function of the received optical power and optical fibre length (considering a fibre loss of α=0.2 dB/km and no dispersion). Results show that the MER only starts to deteriorate at received power levels below -20 dBm or, equivalently, an optical fibre length of 80 km, which is in good agreement with the fibre length value at which the spurious free dynamic range (SFDR) abruptly decreases (see Figure 6). Moreover, for a minimum MER level of 20 dB, the link distance can be increased up to 87.5 km.

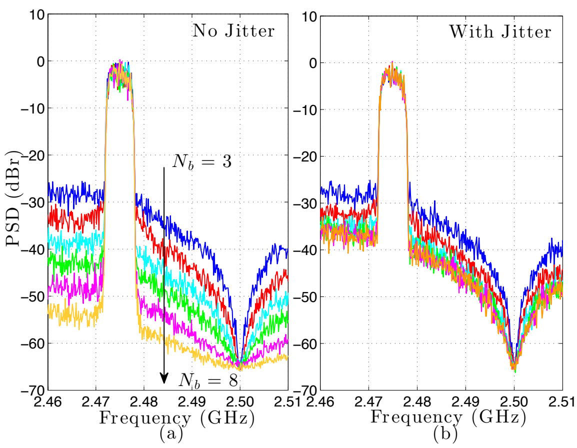

Figure 3: Measured spectra of the DAC output at 2.475 GHz considering a sampling frequency of 125 MHz, different quantisation bits and (a) no jitter and (b) an ADC clock jitter value of 0.8 ps.

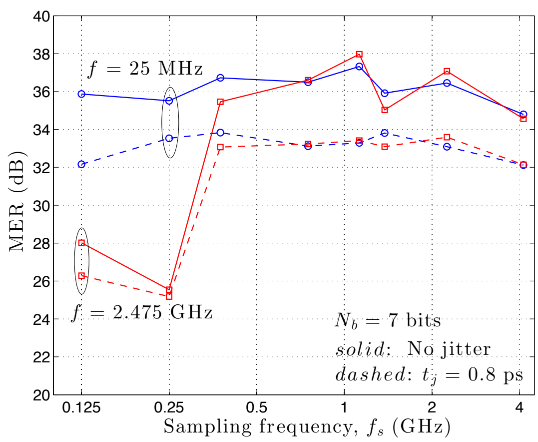

Figure 4: MER vs ADC/DAC sampling frequency, f_s.

3. THE SIGMA-DELTA-OVER-FIBRE SYSTEM

The SDM lays in the group of modulators that use oversampling and a feedback loop to reduce the noise in the band of interest [6]. Additionally, the quantization noise spectrum is shaped and high signal-to-noise ratio (SNR) values in the band of interest may be achieved. The proposed SD-over-fibre (SDoF) systems based on a band-pass SDM [8] is more advantageously applicable to the downlink path since the employment of a DAC at the BS is avoided by using a band-pass filter (BPF). It not only represents a cost and complexity reduction but it also means that future upgrades in terms of increased carrier frequency or modulation format are automatically accommodated. Thus, in the downlink the RF signal is digitised and transported over the optical fibre as a stream of bits, which, as mentioned, provides advantages in terms of IMD and dynamic range.

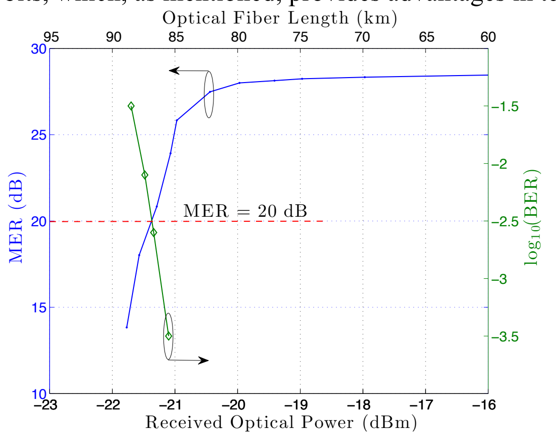

Figure 5: MER vs received optical power and optical fibre length.

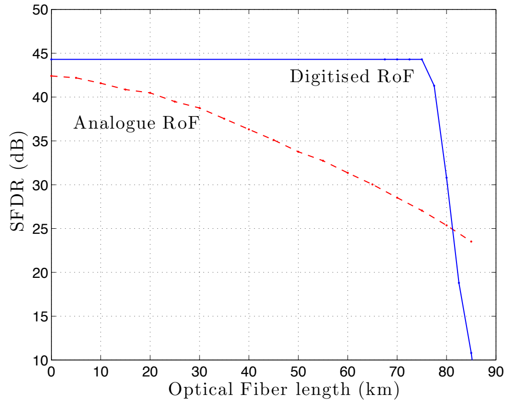

Figure 6: SFDR vs optical fibre length.

Figure 7 shows a possible implementation of the proposed scheme, where the uplink consists of a conventional ARoF scheme, although any desired uplink architecture could be employed. At the CS, all of the analogue blocks such as up/down frequency converters and mixers can be implemented in the digital domain jointly with the SDM in a single platform. Due to the nature of the non-return to zero (NRZ) line code given by the zero-order hold and the sampling process, the spectrum of the digital signal repeats every f_s, where f_s stands for the sampling frequency of the 1-bit ADC of the BP SDM, generating high frequency replicas of the original RF signal (see Figure 8). The bitrate of the SDM is then given by $R_b = f_s \times bit$, enabling the transmission of sub-Gbps digital streams from which RF signals centred at the GHz frequency region can be obtained with no additional frequency up-conversion hardware at the BS.

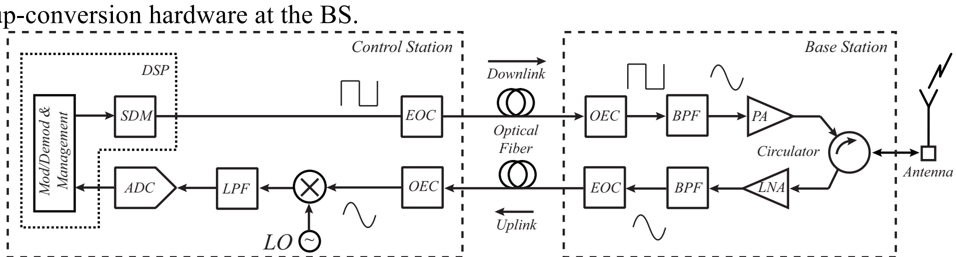

Figure 7: Proposed SDM-over-Fibre architecture with the uplink consisting, as an example of an ARoF scheme.

3.1 Experimental setup and results

The experimental setup used is based on the one illustrated in Figure 2. Here the ADC is a 1-bit 4th order BP SDM, the DAC at the receiver is replaced by a BPF and the pattern detector is replaced by an Agilent DSO90254A oscilloscope with vector signal analysis (VSA) software. The RF signal generated in Matlab conveys 16-QAM symbols centred at 250 MHz which is digitised by the SDM at a sampling frequency of 1 GHz, resulting in a binary rate of 1 Gbps. Figure 9 represents the maximum MER achieved as a function of the VCSEL bias current for 5 MS/s and 10 MS/s signals. As expected, the MER of the former is higher than that of the latter since its oversampling ratio is also higher [8]. Moreover, as the centre frequency increases, the MER decreases due to the NRZ spectrum shape previously referred which induces attenuation and by the relative intensity (RIN) and shot noises that corrupt the analogue signal. Measurements of the VCSEL RIN level were performed at 1.25 GHz and 2.25 GHz and an increase of 5 dB was verified, from −143dB/Hz to −138dB/Hz.

4. DRoF VS SDoF COMPARATIVE ANALYSIS

It is also important to understand how the proposed architecture compares with a conventional DRoF system. Results from section 2 indicate MER values of 28 dB for 2.475 GHz signals considering f_s of 125 MHz and 7 quantisation bits (with no jitter) producing a digital link at an aggregate of 875 Mbps. For a MER of 35.5 dB the sampling frequency would need to be increased to 375 MHz, resulting in a binary rate of 2.625 Gbps. On the other hand, SDoF results reported in section 3 and, more specifically, Figure 9, indicate maximum MER levels of 32 dB at 2.25 GHz using a digital link at 1 Gbps. From these results we can argue that the performance of the proposed SDoF architecture is at least equivalent to that of the conventional DRoF concept, while featuring the above-mentioned advantages, namely avoiding the employment of the DAC at the BS.

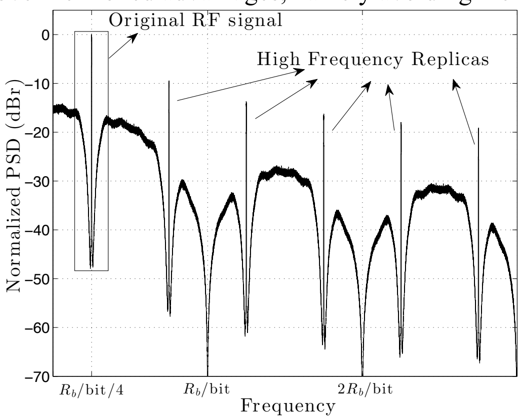

Figure 8: PSD of the BP SDM signal.

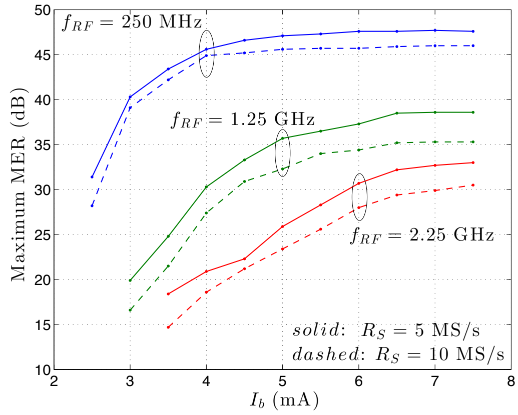

Figure 9: MER vs bias current for R_b = 1Gbps.

5. CONCLUSIONS

In this work the transmission of RF signals in conventional DRoF systems has been presented and evaluated. Results show that the SFDR of DRoF systems remains constant and irrespective of the optical fibre length, provided that the received signal amplitude is above the sensitivity of the link. For our specific scenario (N_b = 6, t_j = 0.8 ps, extinction ratio of 10 dB and VCSEL optical output power of −4 dBm) the SFDR remains constant up to 75 km of optical fibre, allowing the digitisation and transport of 2.45 GHz RF signals using subsampling techniques with constant MER. Additionally, a novel SDM based DRoF architecture was proposed and experimentally evaluated. We conclude that its performance metrics are at least equivalent to the conventional DRoF scheme. Furthermore, the proposed SDoF architecture is economically competitive for either upgrading installed systems as well as for new deployments.

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