Performance Analysis of Radio-over-Fiber Based on Phase-Modulation and Direct-Detection for the Future 5G Network

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ABSTRACT

Access transport network plays a vital role in actual mobile networks to support the need of high data rates, real time services and spectrum efficiency. The future 5G requires an access network with high performances especially in the mm-wave bands. In this work, we propose a radio-over-fiber architecture based on intensity modulation for the downlink and phase modulation for the uplink. This solution permits to cancel optical sources and reduces electrical consumption in the multiple base stations. We focus our study on the phase modulation and direct detection link by evaluation of the quality of the wireless transmitted signal.

Keywords: 5G network, radio-over-fiber, optical phase modulation, filtered-OFDM.

1. INTRODUCTION

The 5G standard requires a high-level spectral efficiency, a high data rate and a short latency making thus the transport networks in front of multiple challenges to provide reliable infrastructure capabilities. Radio-over-fiber (RoF) systems are promising fronthaul technology for the future 5G networks. In the actual mobile networks such as LTE-A, digital RoF links are largely deployed [1][2]. A digital-to-analog signal conversion is required at the photo-receiver front-end. Digitization of high frequency radio signals requires high-speed analog-to-digital and digital-to-analog converters. Analog RoF systems have been studied for home area network coverage extension and radar applications. The proposed architectures are based on Intensity Modulation-Direct Detection (IM-DD) in which the RF signal modulates an optical carrier either by direct laser modulation or external modulation using a Mach-Zehnder modulator. Another solution consists of the phase/frequency modulation RoF links but it requires a frequency discriminator for direct detection or a coherent detection. This makes the Radio Remote Units (RRUs) transceiver more sensitive or complex. But a target design for 5G transport networks is to provide high performances of the signal transmission associated to low power consumption and low complexity.

We propose in this paper, a Phase-Modulation and Direct Detection (PM-DD) RoF architecture only for the uplink channel combined with optical wavelength distribution from a shard station. The complete end-to-end link performances are then studied for the transmitted Filtered-OFDM signal which is a potential waveform candidate for 5G.

2. ARCHITECTURE DESCRIPTION

IM-DD is the simplest and conventional technique for the transmission of the RF signal over optical fiber. In direct modulation scheme, the laser diode is directly modulated by the RF signal. Despite of its advantage, broadband laser is required since high frequency signal is tackled by the fiber chromatic dispersion and the laser chirp. External modulation using a Mach-Zehnder modulator (MZM) permits to avoid chirp effect and several techniques are used to overcome chromatic dispersion penalties. The links based on MZM RoF are preferred for long distance remoting applications. In a PM-DD architecture, the phase of the optical carrier is modulated by the RF signal. This link suffers also from chromatic dispersion and needs an optical filter for direct detection. However, the PM-DD link can offer lower distortion and higher linearity than IM-DD links [3]. In addition, the benefit from PM-DD link is that there is no need to bias the phase modulator. This can be attractive for the multiple RRUs in 5G applications where reduced power consumption and low complexity are targeted. The conversion of the phase modulation to amplitude modulation can be performed by a Mach-Zehnder Interferometer (MZI). For this aim, we propose the RoF architecture represented in Fig. 1 where MZM based RoF link is used for the downlink and phase modulation based RoF link is used for the uplink.

The Central Office (CO) integrates dual-mode laser, optical multiplexer, optical fiber, MZI, photodiode and electrical filter. The wavelength λ_2 is distributed to the RRUs for uplink modulation. The RRU transceiver integrates optical demultiplexer, photodiode, phase modulator, low noise amplifier, electrical circulator and antenna. Thus, no laser source is required at the different RRUs. The simulation method used to analyze the transmission of the OFDM signal over these links is described in [4]. It uses an electrical simulation software.

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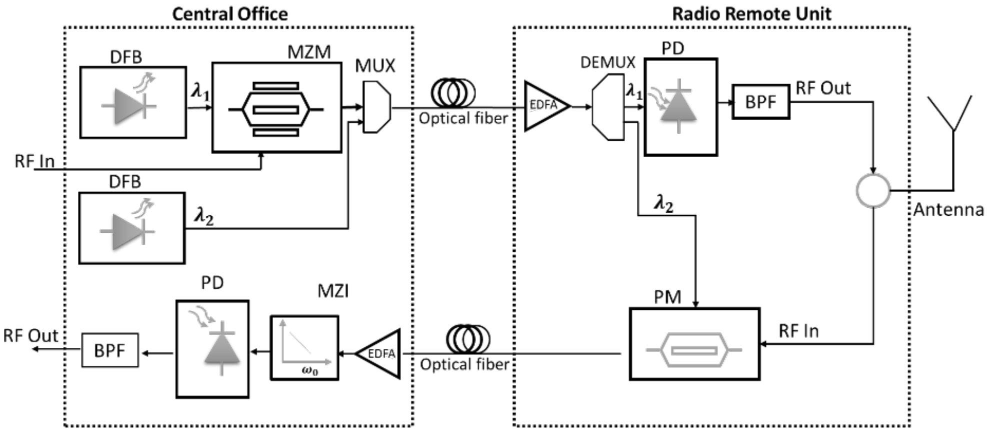
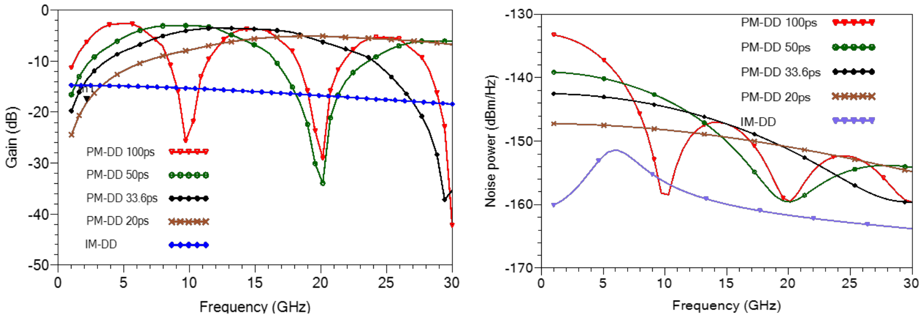


Figure 1. Proposed RoF architecture for 5G transport network.

3. ANALOG PERFORMANCES OF PM-DD RoF LINKS

The RoF system is considered as an analog system regarding to its input and output RF signals. To evaluate analog performances of such link, optoelectronic and optical components are modelled by electrical equivalent circuits to benefit from available and adapted simulation tools of the used software. In this modelling, the optical field is represented by an electrical current. To include realistic behaviour of the components, their models were developed from measurement characteristics [5]. The laser used here is a DFB laser from III-V Lab [5]. This laser has a threshold current of 65 mA and an optical efficiency of 0.3 mW/mA.

Figure 2 represents the link gain and noise power spectral density for PM-DD and IM-DD links. These are obtained for same injected optical power to the modulator and equal half-wave voltage V_π values. It is shown a strong dependence on MZI delay time τ for the case of the PM-DD link. The gain is maximum at RF frequencies multiple of FSR/2, where FSR = 1/τ is the free spectral range. For a frequency of 5 GHz, a maximum link gain of -2.6 dB is achieved with PM-DD link for FSR τ = 100 ps while only -15 dB is obtained with IM-DD link. However, the total noise power is higher with PM-DD link because of the optical phase noise to the intensity noise conversion induced by the frequency discriminator.

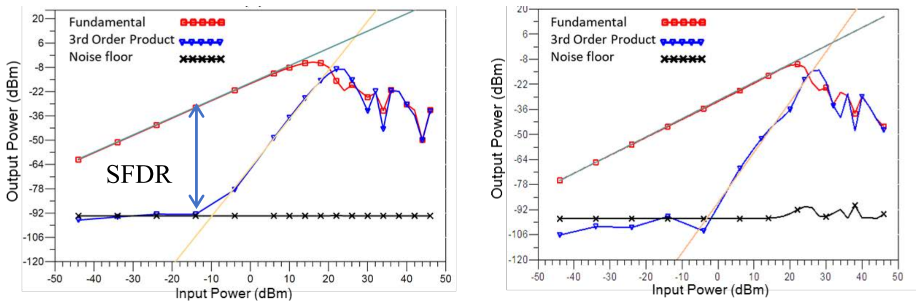


(a) (b)

Figure 2. PM-DD and IM-DD links (a) gain and (b) noise power.

The Spurious Free Dynamic Range (SFDR) has been determined from nonlinear simulation of the third-order intercept point. Figure 3 shows the RoF link output power of the fundamental tone and the third-order intermodulation tone versus the fundamental tone input power at a frequency of 5 GHz. The SFDR is determined graphically from the obtained results and the noise floor. A value of 102.45 dB·Hz$^{2/3}$ has been obtained for PM-DD link and a value of 108.8 dB·Hz$^{2/3}$ for the IM-DD link. Table 1 summarizes some analog characteristics of the two links for a frequency of 2 and 5 GHz. As shown, better performances are obtained with the IM-DD link because of the high noise conversion in the PM-DD link. Therefore, a laser with a narrower linewidth could enhance the performances.

However, the PM-DD performances are interesting for RoF applications and can be a good choice for the uplink. The only drawback is the influence of the laser phase noise and the need of a frequency discriminator. But, high-performance laser and optical filter can be used at the CO because they are shared.



(a) (b)

Figure 3. Dynamic range of (a) IM-DD and (b) PM-DD (τ = 100 ps) links for f_{RF} = 5 GHz.

Table 1. Analog parameters for PM-DD and IM-DD links.

	τ = 100 ps	τ = 50 ps	IM-DD
	f_{RF} = 2 GHz		
Input P_{1dB} (dBm)	13.5	14.9	15.7
Output IP_3 (dBm)	17.26	16.22	10.8
SFDR dB·$Hz^{2/3}$	100.71	103.94	112.6
Noise power (dBm/Hz)	-133.26	-139.29	-158.7
	f_{RF} = 5 GHz		
Input P_{1dB} (dBm)	9.45	16.1	15.7
Output IP_3 (dBm)	16.54	15.02	10.71
SFDR dB.$Hz^{2/3}$	102.45	103.49	108.84
Noise power (dBm/Hz)	-137.13	-140.22	-151.55

4. SYSTEM SIMULATION OF F-OFDM SIGNAL TRANSMISSION OVER PM-DD LINK

Multiple waveforms have been proposed for the future 5G radio access. Most of them was Cyclic Prefix-OFDM (CP-OFDM) or super case of OFDM such as FBMC. The advantages of OFDM are well known and have been studied extensively for the 5G radio access purpose [6]. The choice of 3GPP had finally converged to CP-OFDM techniques. Filtered-OFDM (F-OFDM) is a CP-OFDM variation presented as a potential candidate waveform for the future 5G networks.

4.1 Filtered-OFDM

In F-OFDM case, the expected bandwidth for 5G applications is from 100 to 200 MHz and is divided into several sub-bands. An OFDM modulation with specific numerology is applied for each sub-band. The OFDM signal is then filtered for out of band suppression [7]. Figure 4 shows the complex modulation/demodulation schematic block diagram of F-OFDM signal.

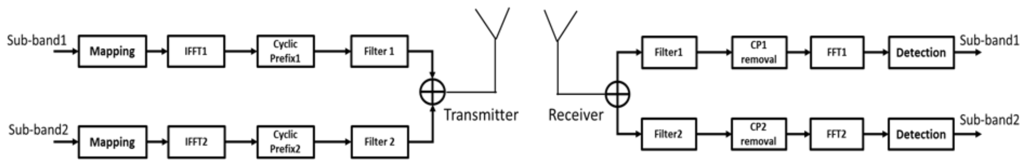


Figure 4. F-OFDM modulation/demodulation scheme.

Table 2 summarizes the main parameters used to generate the F-OFDM signal [8]. Only one sub-band of the OFDM signal is considered here. It is divided into 50 resource blocks, each one formed by 12 subcarriers. The PAPR value of this signal is of 12.14 dB.

Table 2. F-OFDM main parameters.

Parameter	Value
Number of sub-bands	1
Number of FFT points	1024
Number of resource Blocks (RB)	50
Number of subcarrier per RB	12
Cyclic Prefix Length	72
Mapping Constellation	64-QAM
Sampling frequency	100 MHz
Filter Length	512

4.2 Simulation results

The EVM simulations are performed by the co-simulation technique. This method involves the co-simulation of digital and analog signals through adapted interfaces. The EVM is evaluated as function of the OFDM signal power for different values of laser linewidth (adjusted here by the bias current) and optical attenuation. As the PM-DD link suffers from the laser phase noise, a high laser linewidth increases significantly the EVM for low input RF power because of the increase of the noise level as shown in Fig. 5. The laser linewidth for bias currents of 70, 120, 200 and 400 mA is 3 MHz, 310 kHz, 126 kHz and 51 kHz, respectively. For RF power higher than 0 dBm, the EVM increases because of the phase modulator compression reached at these power levels.

The PM-DD link performances are not affected by optical attenuation because the dominant noise is the phase noise conversion process. Regarding the EVM limit for 64-QAM modulation of 8%, the expected input RF power for this link can be in the range of 35 dB (-30 to 5 dBm) for fiber length *L* of 1 and 10 km.

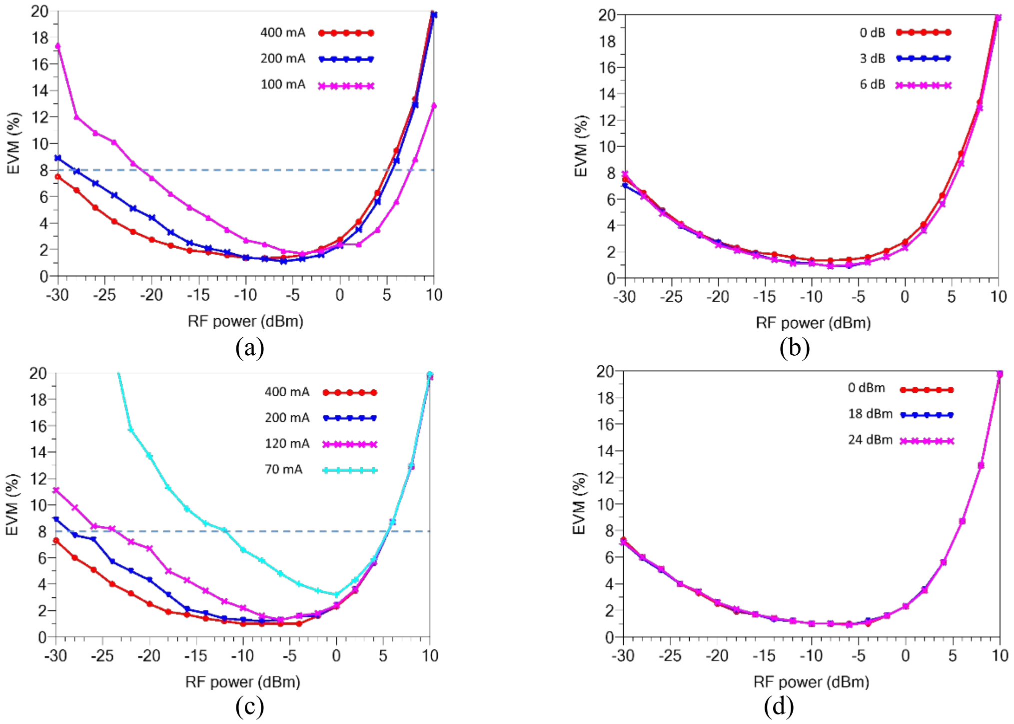


Figure 5. EVM simulation results as function of RF power, laser bias current (I_{bias}) and optical attenuation (A). (a) L = 1 km, A = 0 dB; (b) L = 1 km, I_{bias} = 400 mA; (c) L = 10 km, A = 0 dB; (d) L = 10 km, I_{bias} = 400 mA.

5. CONCLUSION

A radio over fiber system based on IM-DD technique for the downlink and PM-DD technique for the uplink is proposed for the 5G wireless signal transport. The optical power for the uplink modulation is distributed from the central office making thus the base stations laser source free. We used the equivalent circuit models to build the system simulations. These tools allow to evaluate the transmission degradation of F-OFDM signal over the optical link. EVM simulation results have shown that the PM-DD link is affected by the optical phase noise and is less sensitive to optical attenuation which presents a significant advantage for the infrastructure deployment.

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