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Compensation of frequency mismatch between transmitter and receiver local oscillators to enhance 5G-based radio-over-fiber transmissions

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Compensation of frequency mismatch between transmitter and receiver local oscillators to enhance 5G-based radio-over-fiber transmissions

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Abstract. Radio-over-fiber is a cost-effective support for the forthcoming 5G developments aimed to fulfill the ever-increasing demand for information. However, such systems are limited by transmission impairments that reduce the quality of communication. To enhance the system performance, an adaptive decision-feedback equalizer based on the least mean square algorithm is proposed in this work to compensate for frequency mismatch in the transmitter and receiver local oscillators in a radio-over-fiber transmission scenario when considering the latest 5G New radio standard. Simulation results in MATLAB exhibit a major impact from the equalization technique in improving the system performance in the presence of such a frequency offset, allowing the optical link to be extended from ~100 km with no equalizer up to ~690 km after equalization. Thus, it was demonstrated that the proposed adaptive equalization technique is a promising contender to enhance 5G-based Radio-over-Fiber data transmissions.

1. Introduction

High bandwidth consuming applications like ultra-high-quality video broadcasting and virtual reality services are being increasingly incorporated into a new demand profile in which high data rates and low latency are paramount. 5G new radio (NR) is the starting point in the global standardization of the 5th generation of mobile technologies proposed by the 3rd generation partnership project (3GPP) in 2016, which aims to meet the growing demand for information [1]. Radio-over-fiber (RoF) is a promising network architecture for supporting NR requirements and expanding the radio coverage. However, such an approach is normally limited by degradations during the data transmission. One of them is the carrier frequency offset (CFO), which causes the spectral components at the edge of the data signal spectrum to be lost. This effect is due to a frequency mismatch in the transmitter and receiver local oscillators, which leads to intercarrier interference (ICI) in RoF-based data transmissions, giving rise to bit error rate (BER) and error vector magnitude (EVM) poor performance [2].

In related research such as [1], the important role RoF systems have in supporting both backhaul and fronthaul networks in future 5G developments is stated. In [3], orthogonal frequency division multiplexing (OFDM) is depicted as a formidable choice for all link types in NR according to several key performance indicators. Finally, in [4] adaptive equalization is exhibited as an effective technique for optical impairments mitigation.

Thus, in this paper a decision-feedback equalizer (DFE) based on the least mean square (LMS) algorithm is proposed to compensate the CFO in 5G-based OFDM transmissions. By using this method, the frequency disparity in the transmitter and receiver oscillators is corrected, allowing the optical link to be extended from ~100 km with no equalization up to ~690 km after adaptive equalization, achieving bit error rate values below 10^{-9}, thus showing the effectiveness of the proposed equalization method in improving the system performance. The rest of the paper is organized as follows: the methods and parameters used in the simulations are specified in section 2, the simulation results and analysis are described in section 3 while section 4 summarizes the paper and states the major conclusions.

2. Methods and simulation parameters

RoF is generally performed by using intensity modulation with direct detection (IM/DD) in conjunction with OFDM for data transmission purposes, as depicted in Figure 1 from [5]. OFDM transmission starts when data is serial-to-parallel converted and mapped using a modulation scheme. Then, the resulting symbols are modulated onto OFDM subcarriers in an inverse fast Fourier transform (IFFT) block and later rearranged into serial frames allowing for cyclic prefix (CP) insertion, which is generally added for protecting adjacent subcarriers from ICI [6]. Afterwards, the OFDM signal is radio-frequency (RF) modulated by using a local oscillator (LO) before performing the IM/DD transmission.

In the IM/DD transmitter, a laser optical output is intensity-modulated by the RF-OFDM signal through an external device called mach Zehnder modulator. The signal is then sent through a single-mode fiber (SMF) from a central office (CO), and later detected by a photodetector in a base station (BS) from which is amplified and retransmitted through the wireless medium [7]. At the receiver part or customer unit, the same steps in the CO are executed in reverse order, commonly including an equalization stage for compensation purposes in between the FFT, and demodulation scheme blocks to subsequently deliver the resulting data to users. The approach shown in Figure 1 was used in this work to perform the OFDM transmissions, by using the MATLAB’s communication toolbox in [8]. Despite RoF systems usually including both optical and wireless channels in 5G applications, this work was focused on the optical range limitations due to the CFO; hence, the wireless path was not simulated.

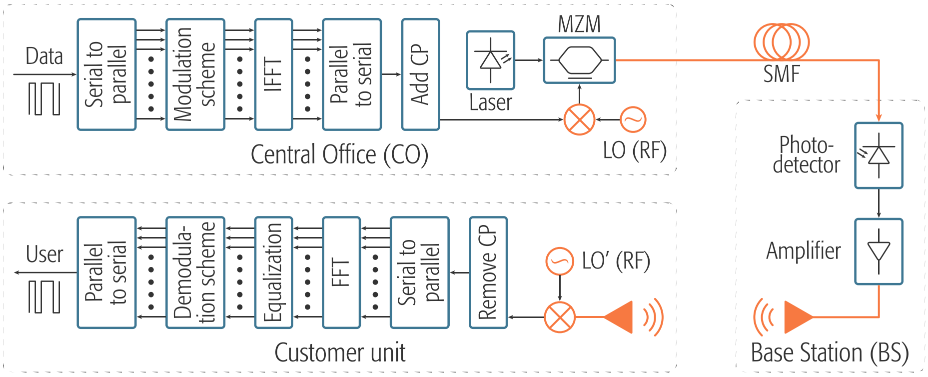


Figure 1. Block diagram of the IM/DD OFDM transmission.

2.1. *Orthogonal frequency division multiplexing waveform*

To generate the OFDM waveform, quadrature phase shift keying (QPSK) was selected instead of higher-order modulation schemes so as to provide a large optical coverage at the expense of a limited bit rate. Moreover, NR brings a variety of OFDM waveform numerologies, as shown in Table 1, from [3]. According to such numerologies, the IFFT block size and the number of CP samples must be kept in any transmission scenario to meet the NR requirements, while the subcarrier spacing, the CP duration and the frequency ranges are variable in order to support a large number of services.

Since forward 5G applications are thought to be contained in the higher RF band, simulations were performed by using a 50 GHz RF carrier, indicating a 240 kHz subcarrier spacing, a 4096-point IFFT/FFT block and 288 CP samples at 0.29 µs [3].

Table 1. Numerologies supported in 5G new radio.

Subcarrier spacing (kHz)	IFFT block size	CP duration (μs)	CP samples	Frequency Ranges (GHz)
15	4096	4.69	288	≤ 6
30	4096	2.35	288	≤ 20
60	4096	1.17	288	≤ 40
240	4096	0.29	288	> 40

2.2. Optical channel

The SMF link was simulated by using the optics wave propagation model presented in [9] and shown in Equation (1), where A represents the amplitude envelope, z is the fiber length and t is the time [9].

$$j\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3}=-\frac{\partial A}{\partial z}. \tag{1}$$

Only second order dispersion $\beta_2 = -21.682\ \mathrm{ps}^2/\mathrm{km}$ and third order dispersion $\beta_3 = 0.117\ \mathrm{ps}^3/\mathrm{km}$ were considered according to an operation wavelength of $\lambda = 1550$ nm, whose value is defined in ITU-T G.652 about the characteristics of a single-mode optical fiber cable [10]. The model made it possible to omit the use of the optical devices illustrated in Figure 1, while preserving the principle of the IM/DD technique. This allowed the transmission to be freed from external noise added by such devices, thus focusing the results on the effects on the information due to CFO.

Furthermore, an additive white gaussian noise (AWGN) channel was modelled by using the normal distribution presented in [11] as shown in Equation (2), where δ is the mean, x is the optical signal output, and σ^2 is the variance.

$$\rho(x)=\frac{1}{\sqrt{2\pi\sigma^2}}\cdot\exp\left(-\frac{(x-\delta)^2}{2\sigma^2}\right). \tag{2}$$

In this model, the parameter δ is typically assumed as zero in electronic systems, while σ^2 takes different values according to $\sigma^2 = P/10^{SNR/10}$, where SNR is the signal-to-noise ratio and P is the signal power of x. The AWGN channel was required in the simulations to determine the achievable transmission coverage when facing optical noise power variation.

2.3. Equalization method

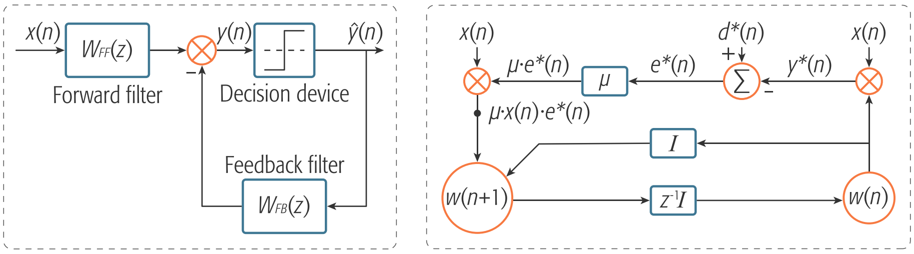
The DFE structure is depicted in Figure 2(a) from [12]. It consists of a forward filter $W_{FF}(z)$ and a feedback filter $W_{FB}(z)$, which compensate the frequency disparity in the transmitter and receiver oscillators by equalizing the symbols affected during the transmission. The forward filter $W_{FF}(z)$ was used to transform the input symbol vector $x(n)$ into equalized symbols $y(n)$ which were then detected by a symbol detector, namely, a decision device, whereas the feedback filter $W_{FB}(z)$ was later fed with such detected symbols $\hat{y}(n)$ to perform the frequency mismatch compensation.

For this purpose, the DF equalizer uses a number of taps, which were updated in this work by using the LMS algorithm according to the Equation (3) from [11], where $w(n+1)$ is the new tap, μ is equalizer convergence and the asterisk denotes the complex conjugate. The error calculation is $e(n) = d(n) - y(n)$, in which $d(n)$ is the desired signal and $y(n)$ is the output signal.

$$w(n+1)=w(n)+\mu\cdot x(n)\cdot e^*(n). \tag{3}$$

The Figure 2(b) illustrates the LMS algorithm signal flow-graph, in which I is the identity matrix and z^{-1} is the unit-time delay operator. It shows that a conjugated output vector $y^*(n)$ is computed in response to the detected DFE symbols $x(n)$. This leads to the error signal generation by subtracting

$y^*(n)$ from $d^*(n)$, while the current symbol $w(n)$ is updated according to the term $\mu \cdot x(n) \cdot e^*(n)$. In this manner, the new equalized symbol $w(n+1)$ is produced to complete the LMS adaptation cycle. The parameter μ was set at 0.01 in the simulations in order to preserve a fast equalizer convergence, whereas the number of feedback and forward taps were set at 8 and 10, respectively.



(a) (a)

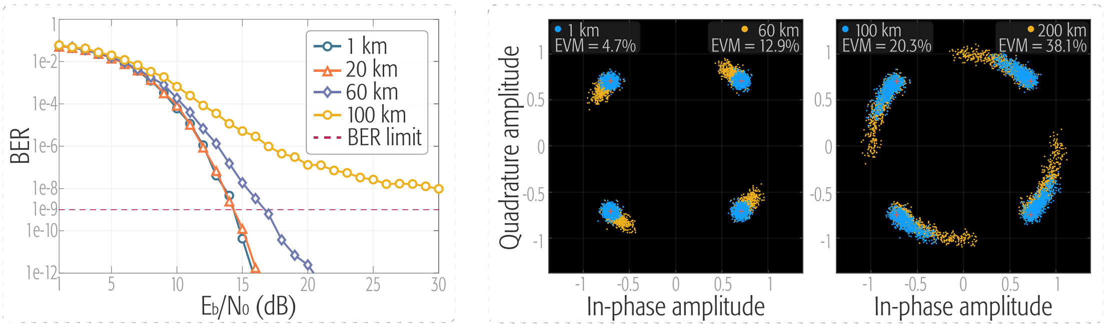
Figure 2. DFE LMS equalization. (a) DFE block diagram, (b) LMS signal flow-graph.

3. Simulation results and analysis

The results were focused on showing how the transmission of an OFDM signal was affected by the CFO in an RoF scenario, whose analysis was carried out in section 3.1, whereas the transmission performance was evaluated before and after equalization in section 3.2.

3.1. Effect of carrier frequency offset

To analyze the CFO impact on the OFDM transmission, Figure 3(a) shows BER curves as a function of E_b/N_0 (energy per bit to noise power spectral density ratio) variation through different fiber lengths stated at 1 km, 20 km, 60 km and 100 km. According to [13], the minimum BER allowed to guarantee a correct transmission in telecommunications is around 10^{-9}. On the other hand, constellation diagrams are presented in Figure 3(b) to qualitatively witness the CFO impairments on the received symbols at 1 km, 60 km, 100 km and 200 km fiber distances with negligible optical noise power. The results are supported by EVM measurements, whose accepted percentage to ensure good quality transmissions with QPSK is below 17.5% for NR as stated in [14].



(a) (b)

Figure 3. CFO effect at different fiber distances. (a) BER vs E_b/N_0 curves at 1 km, 20 km, 60 km and 100 km, (b) Constellation diagrams at 1 km, 60 km, 100 km and 200 km.

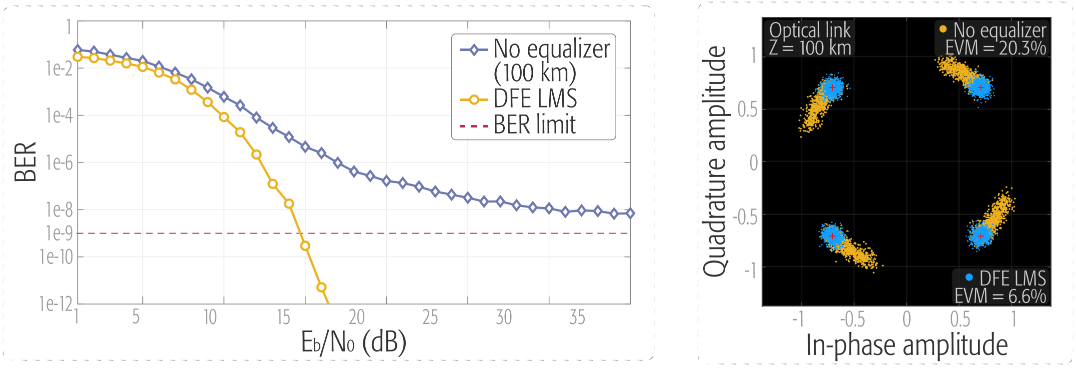
According to Figure 3(a), the transmissions preserved a similar BER performance for all distances up to ~7 dB value, after which the results changed according to each fiber distance. The transmissions at 1 km and 20 km showed similar performance reaching the accepted BER limit at ~14 dB, indicating no significant degradations at such a range. To reach the same BER over 60 km, +3 dB were required, whereas the transmission through the 100 km link showed a decreasing response up to ~25 dB, from which it tended to stabilize at $\sim 10^{-8}$ without achieving the accepted BER limit afterwards.

From the constellation diagrams in Figure 3(b), an irregular frequency response in the form of symbol rotation is observed on the transmitted symbols when using long fiber links, as in this case, at 100 km and 200 km. This effect, namely CFO, is generally allocated to a frequency mismatch in the transmitter and receiver oscillators, which breaks the orthogonality among subcarriers leading to ICI in OFDM transmissions, as explained in literature [2]. Therefore, the transmission through 100 km and 200 km resulted in a low EVM performance due to CFO, whereas a slight affectation was obtained at 1 km and 60 km, preserving an EVM well below the accepted limit, hence ensuring an optimal transmission.

3.2. Carrier frequency offset compensation

The CFO mitigation was performed in this section by using DFE LMS equalization, which permitted to evaluate the OFDM transmission performance before and after compensation according to $\mathrm{E_b/N_0}$ variation in 3.2.1 and based on different fiber distances later in 3.2.2.

3.2.1. Compensation based on E_b/N_0 variation. As it was seen in 3.1, CFO effect was negligible at optical fiber distances between 1 km and 20 km, which corresponds to the standardized range for 5G low latency applications in [15]. Therefore, a more adverse transmission scenario was chosen in this section in which CFO impairments significantly compromised the system performance, allowing the transmission performance to be compared before and after compensation. For that purpose, Figure 4(a) presents OFDM transmission results in the form of BER vs $\mathrm{E_b/N_0}$ curves at 100 km of fiber before and after using DFE LMS equalization. Results without using equalization showed a tendency to stabilize around a BER of 10^{-8}; hence, out of the recommended limit for telecommunications applications. However, a remarkable performance improvement was seen after DFE LMS equalization, making it possible to consolidate the transmission at ~14.5 dB ensuring acceptable BER values.The penalties in the data transmissions through different fiber distances were due to CFO. The constellation diagram in Figure 4(b) shows that the CFO effect causing ICI was completely mitigated at the 100 km fiber link after using DFE LMS equalization, allowing the symbols sent to be maintained at the corresponding constellation points. The aforementioned indicates positive results in the transmission and an EVM performance improvement of 13.7%.



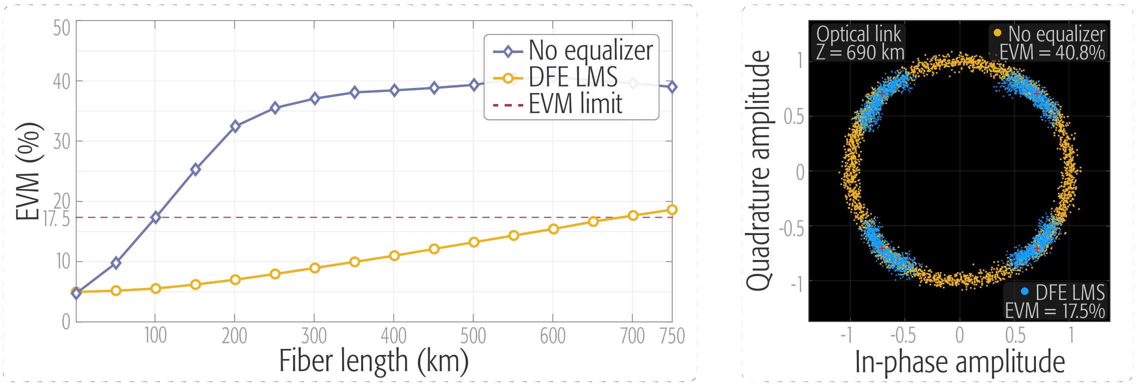
(a) (a)

Figure 4. Carrier frequency offset compensation with and without equalization through a 100 km fiber. (a) BER vs $\mathrm{E_b/N_0}$ curves, (b) Constellation diagram.

3.2.2. Compensation based on different fiber distances. Equalization methods are likely to fluctuate in terms of performance when mitigating transmission impairments at different fiber distances; for this reason, Figure 5(a) presents results in the form of curves of EVM vs fiber distance to evaluate the DFE LMS equalizer performance, and determine to what extend it was possible to expand the optical link range in the OFDM transmission after the CFO compensation.

The information in Figure 5(a) shows that very positive results were obtained, allowing the achievable optical limit to be extended from ~100 km without equalization up to ~690 km after DFE

LMS equalization, ensuring EVM values below the recommended limit (17.5%). To expand the previous information, the resulting constellation diagram at the maximum fiber distance previously mentioned is presented in Figure 5(b) before and after using the DFE LMS equalizer. The most significant degradations were due to CFO, whose distortion factor has been distanced dependent so far. The CFO was largely mitigated after the equalization generating a diagram in which the QPSK constellation points stood clearly distinguishable while achieving a percentage of EVM just at the accepted limit. It should be noted that when appropriate equalization methods are used, the rotation effect observed in Figure 3(b), normally tends to be evenly distributed throughout the constellation points, as shown in Figure 5(b), which in turn positively affects the EVM performance; therefore, the transmission quality.



(a) (a)

Figure 5. Maximum optical range extension after carrier frequency offset compensation. (a) EVM vs fiber length, (b) Constellation diagram at 690 km.

4. Conclusions

In this paper, a decision-feedback equalizer based on the least mean square algorithm was used to compensate for the frequency disparity in the transmitter and receiver local oscillators, which was witnessed as carrier frequency offset in Radio-over-Fiber transmissions when considering the 5G NR standard. Therefore, system performance was compared with and without the aforementioned equalization technique to measure the CFO impact on the OFDM transmissions.

As seen in results from section 3.1, the CFO effect was not significant over the standardized optical range for 5G low latency applications set at (0, 20 km], indicating the validity of the transmission approach simulated. Moreover, the overall simulations showed that the CFO was the most significant degradation affecting the OFDM transmission. Such an effect severely degraded the quality of communication, breaking the orthogonality among OFDM subcarriers and leading to ICI. Simulations also displayed that such an effect increases as fiber distance is longer, compromising the transmission after ~60 km as shown in Figure 3(a). From results in 3.2.1, DFE LMS equalization provided a remarkable improvement in the communication, achieving BER measurements below 10^{-9} at ~14.5 dB through a 100 km fiber link. As a consequence, symbols were maintained at the corresponding constellation points due to an optimal CFO cancellation. Despite most equalization techniques being likely to fluctuate in terms of performance when facing different optical distances, the proposed equalizer exhibited a very uniform response throughout the whole range examined. The latter allowed the achievable optical limit to be extended from ~100 km with no equalizer up to ~690 km after equalization without interruptions.

By using DFE LMS equalization, the frequency mismatch in the transmitter and receiver oscillators seen as CFO was correctly compensated, ensuring correct communications according to BER and EVM measurements. Therefore, it is concluded that the proposed adaptive equalization technique is a promising contender to mitigate CFO and enhance 5G-based radio-over-fiber data transmissions.

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