Transmission of CPRI Signals along Weakly-Coupled Multicore Fibers for Support of 5G Networks

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ABSTRACT
The impact of intercore crosstalk (ICXT) of weakly-coupled multicore fibers on the transmission performance of a Common Public Radio Interface (CPRI) signal in 5G networks is studied by numerical simulation. The results show that forward error correction-supported CPRI signals (accepting higher bit error rates) have more tolerance to ICXT, which increases with the skew between cores. Improvement of the tolerance of CPRI signals to the ICXT, due to the increase of the skew, by 1.7 dB is shown.
Keywords: bit-error rate, intercore crosstalk, multicore fiber, 5G, CPRI.

1. INTRODUCTION

The emergence of 5G and the steady growth of traffic in communication networks [1] led to new proposals on the radio access networks architecture in order to make data transmission more efficient and increase capacity. One of these proposals is the Cloud Radio Access Network [2]-[3] which proposes a physical separation between the base stations units (BBUs) and the transmitter/receiver remote radio-head (RRH) antennas [2]-[3], as shown in Fig. 1. With this new architecture, a new network segment known as fronthaul, which makes the connection between BBU and RRH, is deployed. One way to implement this link is through optical fiber using Radio over Fiber or Digital Radio over Fiber transmission using one of the protocols defined at the Common Public Radio Interface (CPRI) [4] with a bit rate around 10 Gbps [5]. Weakly-coupled multicore fibers (MCFs) are a good solution to support the fronthaul because they can accomplish the bit rate requirements, the fiber availability, the dynamic capacity allocation and the compatibility with the existing and future versions of passive optical networks [4]. However, the transmission in weakly-coupled MCFs, in which cores can be used as independent channels, is affected by intercore crosstalk (ICXT) [6].

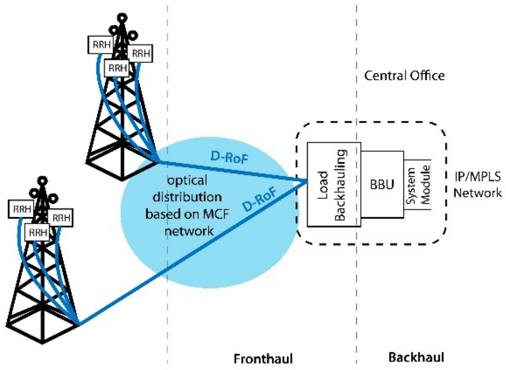

Figure 1. C-RAN architecture with MCFs.

In this work, we investigate, through numerical simulation, the transmission of CPRI signals along weakly-coupled MCFs and how the ICXT affects the transmitted signal performance. The paper is organized as follows. Section 2 presents the simulation model, the estimation of bit error rate (BER) and the type of CPRI signals investigated. Section 3 presents and discusses the numerical results. Section 4 provides the conclusions.

2. SIMULATION MODEL, BER CALCULATION AND CPRI BIT RATES

As a first assessment of the impact of ICXT on the CPRI signal transmission performance, we consider only a single interfering CPRI signal transmitted in core m that may degrade the performance of other similar CPRI signal transmitted in core n. Therefore, as illustrated in Fig. 2, two optical transmitters, each one generating an on-off keying (OOK) signal with the same CPRI bit rate and ideal extinction ratio, are considered.

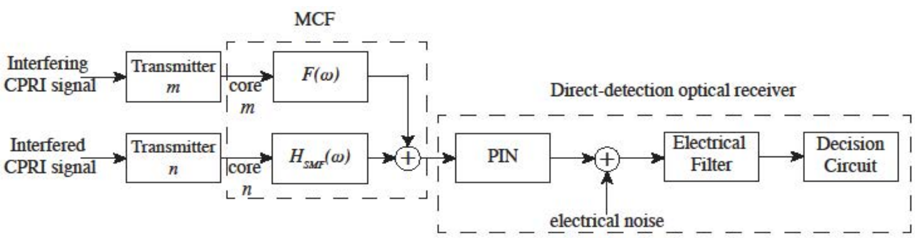

Figure 2. Equivalent system model used to study the impact of ICXT on a 5G fronthaul with direct detection.

Linear single-mode propagation is assumed in each core. The transmission in core n is modelled by the optical fiber transfer function $H_{SMF}(\omega)$ given by $H_{SMF}(\omega)= e^{-j\beta_n(\omega)L}$ where L is the fiber length, ω is the low-pass equivalent angular frequency and $\beta_n(\omega)$ is the intrinsic propagation of core n. A Taylor series expansion up to the second order in ω is considered for $\beta_n(\omega)$, i.e. propagation delay and fiber dispersion effects are considered. The same fiber attenuation is assumed in the two cores. Hence, the fiber attenuation level is not relevant as our analysis considers the receiver sensitivity. The interfering signal in core n resulting from ICXT caused by the signal in core m is obtained using the transfer function [6]:

$$F(\omega)=-jK_{nm}e^{-j\beta_n(\omega)L}\sum_{k=1}^{N_p}e^{-j\Delta\beta_{mn}(\omega)z_k}e^{-j\phi_k} \quad (1)$$

where K_{nm} is the discrete coupling coefficient between cores m and n, $\Delta\beta_{mn}(\omega)$ is the difference of the intrinsic propagation constants of cores m and n, z_k is given by $z_k=(k-1)\,L/N_p+\xi$, with N_p the number of phase-matching points and ξ a random variable uniformly distributed between 0 and L/N_p. ϕ_k is a random variable uniformly distributed between [0,2π] that models random fluctuations in bending radius, twist rate or other conditions of the MCF [6]. The ratio between the crosstalk power at the interfered core (n) output and the power of the signal at the interfering core (m), X_c, is related to the parameters of Eq. 1 by $X_c=N_p|K_{nm}|^2$. The skew between cores m and n is given by $S_{mn}=d_{mn}L$ where d_{mn}, is the walkoff between the cores m and n and is related to Eq. 1 by $\Delta\beta_{mn}(\omega)=\Delta\beta_{0,mn}+d_{mn}\omega-\frac{1}{2}\frac{\Delta D_{mn}\lambda^2}{2\pi c}\omega^2$ [6], where $\Delta\beta_{0,mn}$ is the difference of propagation constants of cores m and n at zero frequency, ΔD_{mn} is the difference of dispersion parameters of cores m and n, λ is the wavelength and c is the speed of light in vacuum. One fiber realization is calculated in each simulation iteration, where the bits of the CPRI signal to be transmitted in core m are randomly generated.

At the optical receiver, the signal at the MCF output is photodetected by a PIN with responsivity of 1 A/W. Then, it is filtered by an electrical filter modelled by a 2nd order Butterworth filter with a cut-off frequency of $0.65\times R_b$, being R_b the bit rate. The electrical noise, referred to the electrical filter input, is characterized by a noise equivalent power of 1×10^{-12} W/$\sqrt{\text{Hz}}$ [7]. After electrical filtering, the decision circuit samples the signal at the time instants $t_k=t_{opt}+kT_b$, where t_{opt} is the optimum sampling time, T_b is the bit period and k = 1, 2, …, N_b, with N_b being the number of bits generated in transmitter n in each simulation iteration, and decides on the transmitted bit.

We use semi-analytical simulation to evaluate the BER [8]. The impact of electrical noise on the performance is taken into account analytically, and the effects of fiber chromatic dispersion and intercore crosstalk on the BER are evaluated using waveform simulation of each simulation iteration. Hence, the BER is given by [8]:

$$\text{BER}=\frac{1}{N_b}\left\{\sum_{\substack{k=1\\ j=0}}^{N_b}Q\left(\frac{F-i_{0,k}}{\sigma_{0,k}}\right)+\sum_{\substack{k=1\\ j=1}}^{N_b}Q\left(\frac{i_{1,k}-F}{\sigma_{1,k}}\right)\right\} \quad (2)$$

where $Q(x)=\frac{1}{\sqrt{2\pi}}\int_x^{+\infty}e^{-\lambda^2/2}\,d\lambda$ [8] and $i_{j,k}$ and $\sigma_{j,k}$ are the mean and standard deviation of the current at the decision circuit input at time instants t_k, conditioned on the transmitted bit j (0 or 1). The decision threshold F is optimized using the bisection method to minimize the BER. Here, $\sigma_{0,k}=\sigma_{1,k}$ as we consider electrical noise only.

In this work, two CPRI bit rates are studied: (i) option 7, with R_b = 9.8304 Gbps, 8B/10B line coding and without Forward-Error Correction (FEC), and (ii) option 8, with R_b = 10.1376 Gbps, 64B/66B line coding and with FEC [4]. For systems without FEC, the target BER is 10^{-12} [4]. For systems with FEC, the target BER depends on the FEC implementation [9]. We assume the FEC implementation with the target BER set to 10^{-3} [9].

3. NUMERICAL RESULTS AND DISCUSSION

In this section, the impact of ICXT on the transmission performance of the CPRI signals is studied by simulation. The simulation parameters that are kept constant throughout this work are the nominal wavelength λ_0=1550 nm, the dispersion parameter D_λ=17 ps/(nm·km) (the same for both cores), the number of simulated OOK bits per fiber realization $N_b=2^9$, the N_p=1000, the fiber length L=20 km and $\Delta\beta_{0,mn}$=0.

First, we start by studying the number of fiber realizations that are necessary to achieve a stabilized value of the average BER. To provide a certain margin for BER degradation due to ICXT, we set the BER in the absence of ICXT to two orders of magnitude lower than the target BER. Hence, our studies for line option 8 consider the BER of 10^{-5} in the absence of ICXT. Following the same reasoning for systems without FEC, the BER in absence of ICXT is 10^{-14}. Figures 3a) and 3b) depict the BER for each MCF realization and the average BER as a function of the number of fiber realizations for d_{mn} = 1 ps/km. Figure 3a) refers to the CPRI signal with the bit rate of 9.8304 Gbps (which does not consider FEC and the BER without ICXT is 10^{-14}). The crosstalk level is X_c = −30 dB. Figure 3b) refers to the CPRI signal with R_b = 10.1376 Gbps (which considers FEC and the BER without ICXT is 10^{-5}) and X_c = -15 dB. These crosstalk values are chosen to lead to an average BER degradation relative to the one in absence of ICXT by about two orders of magnitude. Figure 3a) shows that the average BER can be considered stabilized after about 4000 MCF realizations. In the subsequent studies for the CPRI signal with 9.8304 Gbps, we have set the number of fiber realizations to 10^4 as a conservative choice. Figure 3b) shows that the average BER is nearly stable after 400 MCF realizations. For the subsequent studies, we have set the number of MCF realizations to 10^3 as a conservative choice for the CPRI signal with 10.1376 Gbps. We have verified that the mentioned numbers of fiber realizations are more than sufficient to lead to a stabilized average

BERs for different crosstalk levels, different fiber lengths (other than 20 km), different walkoffs between the fiber cores and CPRI signals with different bit rates. The difference between the number of fiber realizations leading to a stabilized average BER is attributed to the order of magnitude of the average BERs considered in Fig. 3a) and 3b).

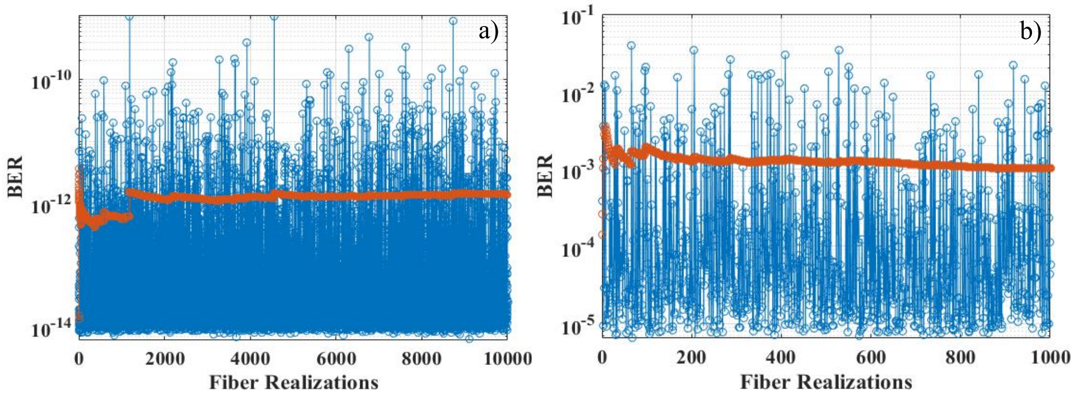

Figure 3. BER for each MCF realization (blue symbols) and average BER (red symbols) as a function of fiber realizations. In a), R_b=9.8304 Gbps, X_c= −30 dB and BER in the absence of ICXT is 10^{-14}. In b), R_b=10.1376 Gbps, X_c= −15 dB and BER in the absence of ICXT is 10^{-5}.

Figures 3a) and 3b) show that the randomness of the ICXT mechanism leads to a strong variation of the BER per fiber realization. The BER can be degraded severely or even improved. In Fig. 3a), the best BER obtained per fiber realization is 6.3×10^{-15} and the worst BER is 1.1×10^{-9}. Figure 3b) exhibits a best BER of 6.3×10^{-6} and a worst BER of 3.9×10^{-2}. The eye-patterns corresponding to these BERs per fiber realization are presented in Fig. 4 where the ICXT impact on the eye-patterns can be seen. These eye-patterns do not show the effect of the electrical noise to make clear the ICXT effect. Figures 4a) and 4d) correspond to the cases where no ICXT is present. As the bit rates are similar in these plots, no significant difference is observed between the two eye-patterns. Figures 4b) and 4e) show the eye-patterns corresponding to the improvement of BER due to ICXT relative to the case of absence of ICXT. Figures 4c) and 4f) correspond to the MCF realizations in which the worst BER occurs. Figure 4c) shows that the eye-closure for the worst BER realization is not as severe as the one obtained in Fig. 4f). This justifies the higher number of MCF realizations needed to get a stabilized average BER for lower BERs [see Fig. 3a)], since any slight signal distortion caused by ICXT can degrade the average BER a few orders of magnitude. For higher BERs [see Fig. 3b)], a higher crosstalk level is necessary to close the eye-pattern significantly in order to get BERs per fiber realization with a few orders of magnitude above the reference BER of 10^{-5}. Analysis of Fig. 4a), 4b) and 4c) [and extending the same analysis to Fig. 4d), 4e) and 4f)] reveals that the impact of the ICXT on the eye-pattern is felt only at the amplitudes of bit '1' while, at bit '0', the amplitude values remain essentially the same.

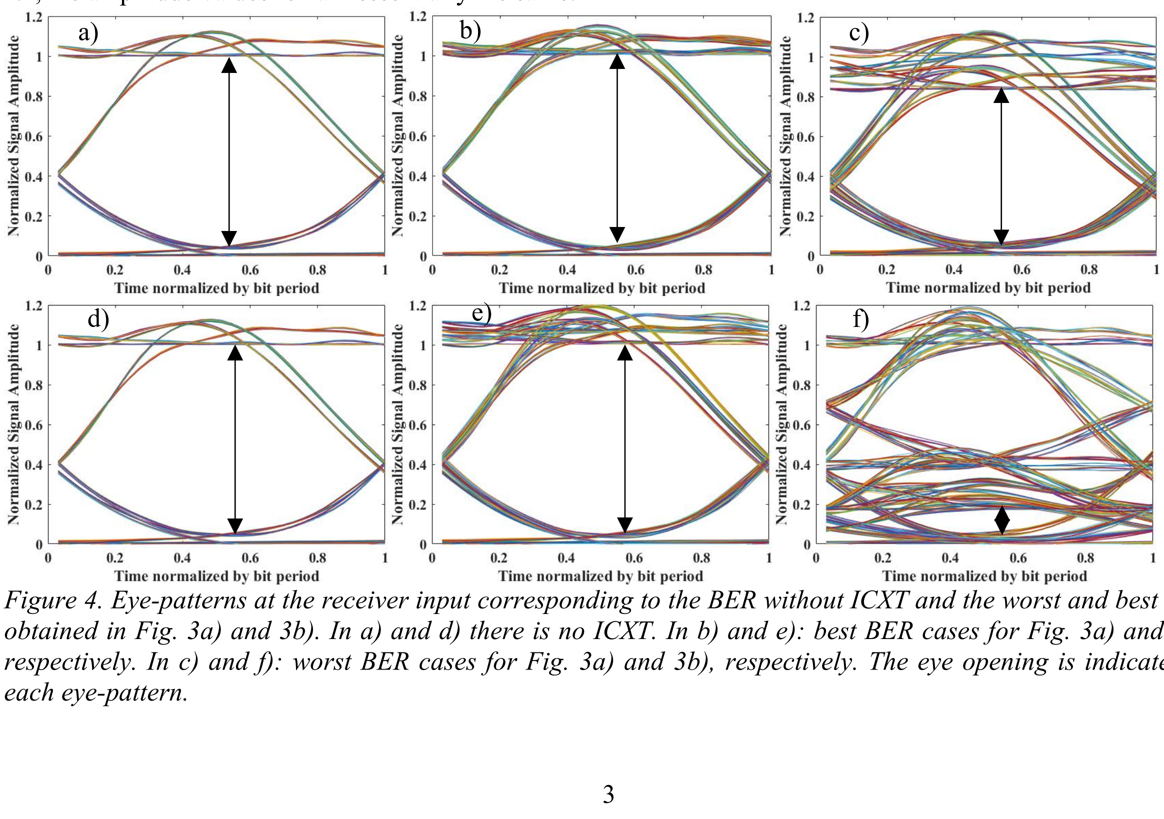

Figure 4. Eye-patterns at the receiver input corresponding to the BER without ICXT and the worst and best BER obtained in Fig. 3a) and 3b). In a) and d) there is no ICXT. In b) and e): best BER cases for Fig. 3a) and 3b), respectively. In c) and f): worst BER cases for Fig. 3a) and 3b), respectively. The eye opening is indicated in each eye-pattern.

After having established the number of MCF realizations required to reach a stabilized value of the average BER, the performance degradation imposed by the increase of the crosstalk level is investigated. Figure 5 depicts the average BER as a function of the crosstalk level, for d_{mn} = 1 ps/km and d_{mn} = 50 ps/km. These values of walkoff correspond to two distinct levels of skew: one (d_{mn} = 50 ps/km), much higher than the bit period and other (1 ps/km) much lower than the bit period. Figure 5a) corresponds to the CPRI signal with 9.8304 Gbps and Fig. 5b) relates to the CPRI signal with 10.1376 Gbps. As expected, the BER becomes higher with the increase of the crosstalk level. In Fig. 5a), as the BER without ICXT is very low (10^{-14}), lower values of X_c lead to a significant BER degradation. An average BER of 10^{-12} is reached for X_c = -30 dB and X_c = -28.3 dB, for d_{mn} = 1 ps/km and for d_{mn} = 50 ps/km, respectively. In Fig. 5b), as the BER without ICXT is higher (10^{-5}), higher ICXT levels are required to degrade the average BER. An average BER of 10^{-3} is reached for X_c = -15 dB and X_c = -13.7 dB, for d_{mn} = 1 ps/km and d_{mn} = 50 ps/km, respectively. The reduction of the impact of ICXT with the increase of the skew between the cores d_{mn} is in qualitative accordance with the results presented in [10].

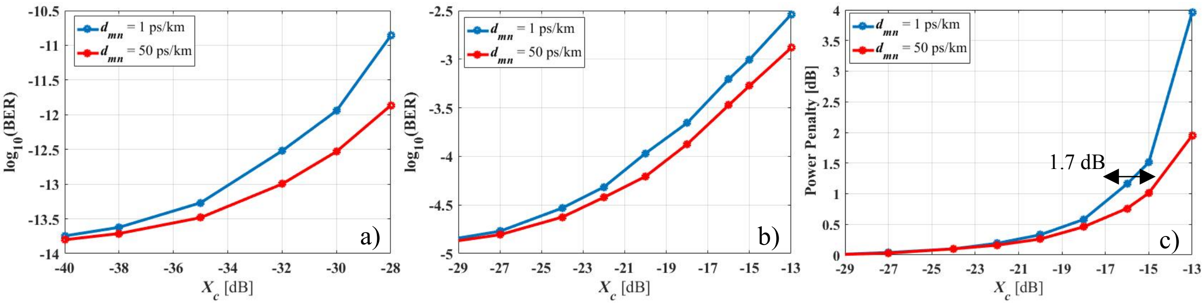

Figure 5. In a) and b), BER as a function of crosstalk level, X_c in dB, for d_{mn} = 1 ps/km (blue line) and *d_{mn} = 50 ps/km (red line). In a), CPRI signal with R_b = 9.8304 Gbps; in b), CPRI signal with R_b = 10.1376 Gbps. In c), power penalty as a function of crosstalk level X_c for a BER of 10^{-3} and R_b=10.1376 Gbps for d_{mn} = 1 ps/km (blue line)* and *d_{mn} = 50 ps/km (red line).*

We estimate also the system power penalty due to ICXT for the 10.1376 Gbps CPRI signal with BER = 10^{-3} and the two levels of skew. Fig. 5 c) show the results obtained. For d_{mn} = 1 ps/km, a power penalty of 1 dB occurs for an ICXT level of -16.7 dB and, for d_{mn}= 50 ps/km, a power penalty of 1 dB occurs for a ICXT level of -15 dB. Therefore, we conclude that the skew effect can improve the tolerance of CPRI signals to the ICXT by 1.7 dB.

4. CONCLUSIONS

We have investigated the weakly-coupled MCF ICXT impact on the CPRI signal transmission performance in a 5G network. The results have shown that FEC-supported CPRI signals (accepting higher BER) have more tolerance to ICXT, which increases with the skew enhancement between cores. Improvement of the tolerance of CPRI signals to the ICXT, due to the increase of the skew, by 1.7 dB has been shown.

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