Impact of Receiver Non-idealities on a Full Duplex Spatial Modulation System Performance

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***Abstract*—In this paper, we analyze, for the first time, the performance of a full-duplex system combined with spatial modulation technique in presence of the receiver non-idealities. IQ imbalance and phase noise are the two radio front-end mismatch factors that have been considered. The impact of the IQ imbalance on the bit error rate (BER) performance of the full-duplex spatial modulation (FDSM) system under different noise levels is investigated. An estimator has also been proposed for the self-interference cancellation (SIC) after the imperfect receiver. The results show that IQ imbalance does not significantly reduce system BER performance at low signal-to-noise ratios. Moreover, it is shown that the proposed estimator is able to maintain the system at an acceptable BER.**

***Index Terms*—Spatial Modulation, Full Duplex, Channel Estimation, IQ imbalance, Phase noise**

I. Introduction

The shortage of spectrum resources is one of the key factors that restrict the development of the mobile communications technology. Full duplex (FD) communications has been developed to overcome this problem since it can double the radio link data rate and the spectral efficiency through simultaneous and bidirectional communication [1]. The main challenge of FD systems is self-interference (SI), which is caused by the coupling of the transmitting antenna with the receiving one. SI can be even more challenging in multi-antenna systems.

In recent years, spatial modulation (SM) has been proposed as a new Multiple-Input Multiple-Output (MIMO) transmission technology [2]. SM solves the drawbacks of MIMO systems such as strong inter-channel interference (ICI), high power consumption and systems complexity due to multiple radio frequency (RF) chains. SM uses only one RF chain in the transmitting end and applies the active state of antennas as a support for the transmission of information. In this case, SM can maintain efficiency as well as reduce ICI and the spectrum congestion.

The performance of the SM system depends on the availability of channel state information (CSI) estimation accuracy. A complete SM system with a CSI detector has been studied in [3]. The results indicate that the bit error rate (BER) performance of the SM system can be kept at an acceptable level in multi-paths channel environments.

The combination of FD and SM is a new area that has drawn significant attention recently. Some theoretical attempts to combine these two techniques have been made in [4] and [5]. The full duplex spatial modulation (FDSM) system can preserve the superiority of transmission efficiency in SM and FD systems. Meanwhile, only one SI path is generated during each symbol transmission period, which makes self-interference cancellation (SIC) more efficient.

In general, impairments of the radio front-end such as in-phase and quadrature (IQ) imbalance and phase noise strongly affect the transmission performance. For FD systems, the strength of residual SI after SIC directly influences the quality of the transmission. Moreover, receiver non-idealities will affect the accuracy of the SI estimation, which also have an impact on system performance. Digital estimation and compensation of IQ imbalance for FD system is presented in [6] and [7]. As the SI signal is much stronger than the signal of interest, the influence of the receiver non-idealities on SI signal will significantly increase the system's BER. The authors of [8] proved that IQ imbalance is also a critical issue for SM-based transmission. In [9] the performance of a SM system in presence of IQ imbalance has been studied via computer simulations and analytical derivations.

However, to the best of the authors' knowledge, there is no previous work considering the impact of the receiver non-idealities on the FDSM system. Moreover, no estimation and compensation approaches for strong SI with impairments are proposed for FDSM systems. Channel estimation and SIC are still open problems for FDSM systems, especially in presence of receiver non-idealities.

The disparities of the characteristics of components constituting the radio front-end induce IQ imbalance and phase noise, which are the two main factors causing receiver non-idealities.

In this paper, we study 2×2 FDSM systems over a Rician fading channel in the presence of radio front-end non-idealities. We design a new receiver structure to cope with IQ imbalance and phase noise for this FDSM system.

The remainder of this paper is divided as follows: in Section II, the 2×2 FDSM system model is introduced. Also, the receiver and the SI estimation algorithm are explained in detail. Section III presents a comparison between the BER performance of system with different levels of non-idealities and no receiver imperfection. Section IV concludes this paper and gives some future directions of this work.

II. System Modeling

Both nodes of the FDSM system (defined as node A and node B) have emitting and receiving capabilities. The structure of Node A in the 2×2 FDSM system is given in Fig. 1. The incoming data bitstream is divided into groups of $\log_2(N_t M)$

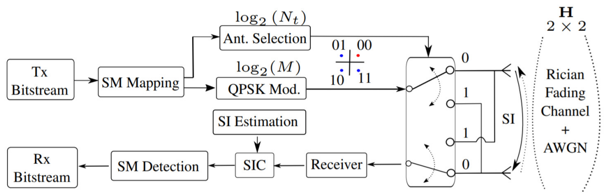


Fig. 1. 2×2 Full Duplex Spatial Modulation system: node A

bits. N_t represents the number of antenna at each node, M represents the modulation order of the complex constellations. For the SM mapping, $\log_2(N_t)$ bits are used to select the transmitting antenna.

In the particular case studied here, $N_t = 2$ and $M = 4$. Depending on the incoming bit combination, an analog switch selects one of the two antennas. The antenna that is not selected is used for signal reception. The other $\log_2(M)$ bits determine the symbol of the quadrature amplitude modulation (QAM) modulation. In our case, 4-QAM or quadrature phase-shift keying (QPSK) modulation is employed. The transmitted signal passes through a 2×2 sized Rician fading channel modeled by the matrix $\mathbf{H}$. Moreover, the presence of average white gaussian noise (AWGN) η is considered.

We suppose that node A and node B transmit simultaneously over the same communication channel. At node A, while transmitting the modulated signal, the second antenna receives the signal from the node B together with the SI signal. Consequently, the received signal from node B experiences a strong interference. The incoming signal together with the SI one are transposed in baseband by an analog radio front-end supposed to be impacted by IQ imbalance and phase noise.

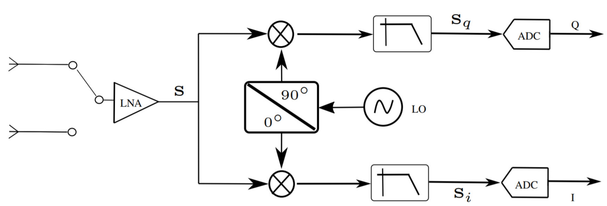


Fig. 2. 2×2 Full Duplex Spatial Modulation system: radio front-end of the receiver

The simplified architecture of the receiver's analog radio front-end is shown in Fig. 2. In practice, the total gain on the in-phase I and quadrature Q paths of the radio front-end RF are not exactly equal. Similarly, the 90° phase shift of the local oscillator (LO) for the Q path may also be inaccurate. When the analog part of the radio front-end does not respect the power balance and the orthogonality between the I and Q branches, IQ imbalance occurs. The IQ imbalance can be described by two parameters: the amplitude imbalance ε and the phase orthogonality imbalance θ. A more exhaustive presentation of IQ imbalance is given in [10].

The deformation of a QPSK constellation in presence of different IQ imbalance levels is shown in Fig. 3. For an amplitude imbalance ε and a phase orthogonality imbalance θ, a θ-angle and ε-dB deformation will occur. In this case, 4 dB and 20° are selected as the absolute value of the gain imbalance and the phase imbalance respectively. It should be noticed that for real transmissions, the IQ imbalance is much smaller.

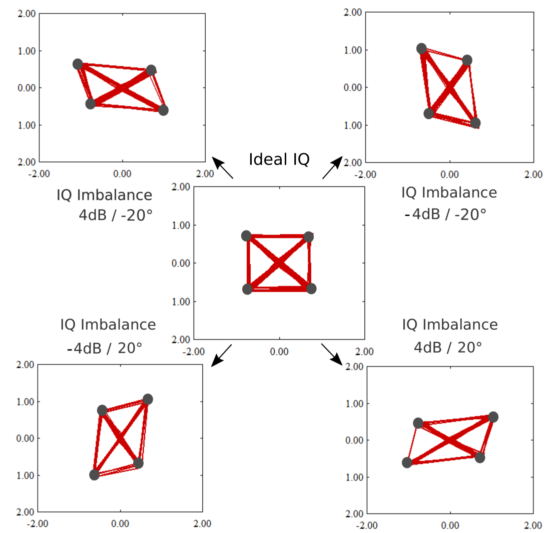


Fig. 3. Deformation of a QPSK constellation in presence of different scenarios of IQ imbalance

The other parameters (the nonlinear behavior of the amplifiers or the mixers, the quantization noise brought by the Analog to Digital Converters (ADC), the phase noise of the local oscillator, etc.) may degrade the performance of the radio front-end. In our case, the impact of the phase noise $\phi(t)$ is considered as the most critical one.

$\mathbf{S}$ is the incoming mixed signal, the signals $\mathbf{S}_i$ and $\mathbf{S}_q$ impacted by the gain and phase imbalance and by phase noise in time domain are given by (1):

$$\begin{cases} \mathbf{S}_i = \left(1 + \dfrac{\varepsilon}{2}\right) \cos\left(\omega_c t + \dfrac{\theta}{2} - \phi(t)\right) \cdot \mathbf{S} \\ \\ \mathbf{S}_q = \left(1 - \dfrac{\varepsilon}{2}\right) \cos\left(\omega_c t - \dfrac{\theta}{2} - \phi(t)\right) \cdot \mathbf{S} \end{cases} \tag{1}$$

where $\omega_c = 2\pi f_c$, and f_c is the frequency of the receiving signal.

As the SI signal strength is higher than the useful one (the one transmitted by the remote node B), the impact of IQ imbalance and phase noise on system performance mainly comes from its impact on SI signal.

SIC is implemented after the frequency translation (in baseband). A least-squares (LS) estimator is proposed for cancelling the SI together with impact of the receiver non-idealities on SI. More precisely, the SI channel and the non-idealities are not actually separated, the two parameters are estimated at the same time.

During the estimation phase, we assume that only the SI signal is present and Node B does not transmit. The estimated channel matrix $\widetilde{\mathbf{H}}^*$ between the generating SI signal $\mathbf{x}$ and the receiving signal $\mathbf{y}$ is given by (2):

$$\widetilde{\mathbf{H}}^{*} = \frac{1}{N^2} \cdot \left[\mathbf{x^t} \cdot \mathbf{x^t}^H\right]^{-1} \cdot \overline{\mathbf{y^t} \cdot \mathbf{x}}^{-1} \tag{2}$$

where:

$$\begin{cases} \mathbf{x} = [x[0], \quad x[1], \quad \cdots \quad x[N-1]]^t \\ \mathbf{y} = [y[0], \quad y[1], \quad \cdots \quad y[N-1]]^t \end{cases} \tag{3}$$

and:

$$x[n] = A(n)e^{j\varphi_{si(n)}}. \tag{4}$$

Here A, φ_{si} represent the amplitude and the phase of the SI signal, respectively. N is the number of symbols that are employed for the SI estimation. The operator $[\,\cdot\,]^t$ corresponds to the matrix transpose, $[\,\cdot\,]^H$ corresponds to the Hermitian transpose and $\overline{[\,\cdot\,]}$ means the complex conjugate.

Consider $\mathbf{H}_{si}$ the real SI channel and $\mathbf{H}_{in}$ the channel taking into account the non-idealities. The theoretical relation $\mathbf{H}^*$ between $\mathbf{x}$ and $\mathbf{y}$ is:

$$\begin{aligned} \mathbf{H}^*(n) = \mathbf{H}_{si}(n) \cdot \mathbf{H}_{in}(n) = \mathbf{H}_{si}(n) \cdot ((1+\tfrac{\varepsilon}{2}) \\ \cos(\omega_c t + \tfrac{\theta}{2} - \phi(t)) + j(1-\tfrac{\varepsilon}{2})\cos(\omega_c t - \tfrac{\theta}{2} - \phi(t))) \end{aligned} \tag{5}$$

As stated, compared to the main signal transmitting from the other node, the SI signal strength is much higher, so even a small IQ imbalance on the SI signal can have a great impact on the system's performance. We propose an estimation after the receiver front-end, because the impact of non-idealities on SI can be also suppressed. The difference between the estimation of channel before ($\widetilde{\mathbf{H}}^{*\mathbf{1}}$) and after the receiver front-end ($\widetilde{\mathbf{H}}^{*\mathbf{2}}$) is taking into account the non-idealities.

$$\begin{aligned} \widetilde{\mathbf{H}}^{*\mathbf{1}} &= \widetilde{\mathbf{H}}_{\mathbf{si}}(\mathbf{n}) \\ \widetilde{\mathbf{H}}^{*\mathbf{2}} &= \widetilde{\mathbf{H}}_{\mathbf{si}}(\mathbf{n}) \cdot \widetilde{\mathbf{H}}_{\mathbf{in}}(\mathbf{n}) \end{aligned} \tag{6}$$

The two different residual signals are given in the equation (7) and the equation (8). $\mathbf{S}_r^1$ and $\mathbf{S}_r^2$ represent residual signal for the estimation before and after the receiver front-end respectively. Here B, φ_s are the amplitude and the phase of the useful signal from node B, respectively. For the first case, the coefficient ρ_1 of the SI signal cannot be completely eliminated. However, it can be seen that the non-negligible influence of the impairments on the SI signal can be eliminated in the second case under ideal conditions ($\rho_2 = 0$). Therefore, with an ideal estimation, the mixed signal after SIC has the same power level as the signal of interest, which means the BER performance of the FDSM system with cancellation will be at the same level as the SM system.

$$\begin{aligned} \mathbf{S}_r^1(n) &= A(n)e^{j\varphi_{si}(n)} \cdot \mathbf{H}^*(n) + B(n)e^{j\varphi_s(n)} \cdot \mathbf{H}_{\mathbf{in}}(n) \\ &\quad - A(n)e^{j\varphi_{si}(n)} \cdot \widetilde{\mathbf{H}}^{*\mathbf{1}} \\ &= A(n)e^{j\varphi_{si}(n)}(\mathbf{H}^*(n) - \widetilde{\mathbf{H}}^{*\mathbf{1}}) + B(n)e^{j\varphi_s(n)} \\ &\quad \cdot \mathbf{H}_{in}(n) \\ &= A(n)e^{j\varphi_{si}(n)}\overbrace{(\mathbf{H}_{si}(n) \cdot \mathbf{H}_{in}(n) - \widetilde{\mathbf{H}}_{\mathbf{si}}(\mathbf{n}))}^{\rho_1} \\ &\quad + B(n)e^{j\varphi_s(n)} \cdot \mathbf{H}_{in}(n) \end{aligned} \tag{7}$$

$$\begin{aligned} \mathbf{S}_r^2(n) &= A(n)e^{j\varphi_{si}(n)} \cdot \mathbf{H}^*(n) + B(n)e^{j\varphi_s(n)} \cdot \mathbf{H}_{\mathbf{in}}(n) \\ &\quad - A(n)e^{j\varphi_{si}(n)} \cdot \widetilde{\mathbf{H}}^{*\mathbf{2}} \\ &= A(n)e^{j\varphi_{si}(n)}(\mathbf{H}^*(n) - \widetilde{\mathbf{H}}^{*\mathbf{2}}) + B(n)e^{j\varphi_s(n)} \\ &\quad \cdot \mathbf{H}_{in}(n) \\ &= A(n)e^{j\varphi_{si}(n)}\overbrace{(\mathbf{H}_{si}(n) \cdot \mathbf{H}_{in}(n) - \widetilde{\mathbf{H}}_{\mathbf{si}}(\mathbf{n}) \cdot \widetilde{\mathbf{H}}_{\mathbf{in}}(\mathbf{n}))}^{\rho_2} \\ &\quad + B(n)e^{j\varphi_s(n)} \cdot \mathbf{H}_{in}(n) \end{aligned} \tag{8}$$

Moreover, the four symbols of the QPSK modulation are impacted by IQ imbalance in different ways. For example, for a positive amplitude mismatch and a clockwise phase mismatch, the amplitudes of symbols in the first and third quadrants increase and the phase shifts rotate in a counter-clockwise direction. The symbols in the second and fourth quadrants change in opposite direction. Hence, a judgment on the quadrant where the symbol is located is also necessary before the SIC module.

The remaining signal after SIC will pass through a SM detection module to detect the transmitting antenna and symbol. We assume that a perfect CSI of the Rician fading channel between node A and node B can be obtained in this article to ensure SIC quality as the single variable for judging system performance. A CSI estimation method for this Rician fading channel is explained in [3]. Finally, the output bitstream is generated by combining the transmitting bits coded by the antenna selection and coded by the QPSK modulation.

III. Numerical results

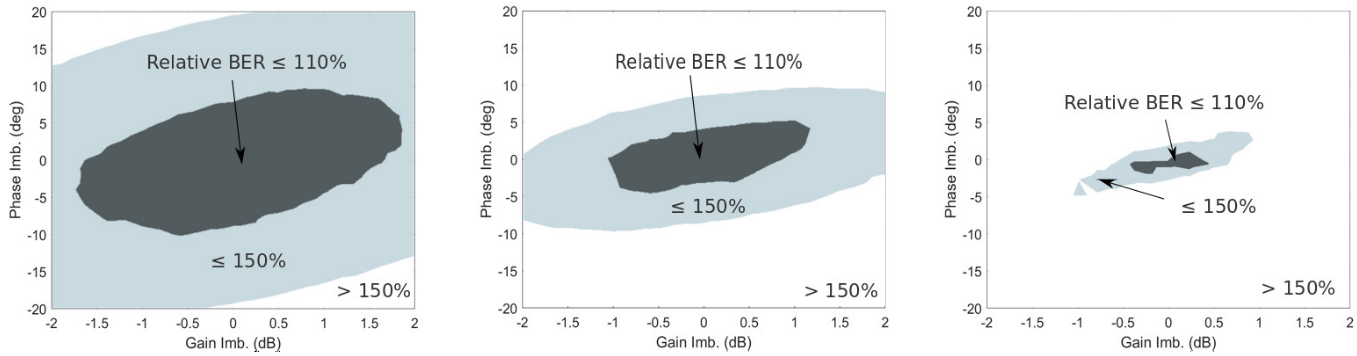
A FDSM simulator based on Keysight's ADS and Matlab software is built in order to test the performance of the FDSM system. The performance in the presence of non-idealities at the receiving end is analyzed by taking into account: the impact of the IQ imbalance under different noise levels, the BER performance with estimation under IQ imbalance, and the BER performance under different phase noise levels. The system parameters of this simulation framework are as follows: carrier frequency = 2.4 GHz, bandwidth = 10 MHz. Moreover, a time-varying Ricean fading channel environment with $K = 1$ and QPSK modulation are applied.

A. *Impact of IQ Imbalance*

The impact of IQ imbalance under different ratios of Energy per Bit (E_b) to the Spectral Noise Density (N_0) is studied in this part. An ideal SI detector is supposed at this point. The system's BER performance without IQ imbalance under E_b/N_0 = 10, 15 and 20 dB is shown in Table I.

TABLE I
System Performance with ideal IQ

E_b/N_0	Number of symbols	BER
10	10 000	0.04459
15	10 000	0.01147
20	10 000	0.00040



(a) Eb/No=10 dB (b) Eb/No=15 dB (c) Eb/No=20 dB

Fig. 4. Relative BER under Eb/No=10 dB, 15 dB and 20 dB.

The FDSM system performance within the corresponding range of the gain and phase imbalance has been evaluated. The variation of the gain imbalance is (-2dB, 2dB) and the variation of the phase imbalance is (-20°, 20°). This range selection is large enough to cover the IQ imbalance of commercial RF front-ends.

The relative BER (ratio between BER with IQ imbalance and BER with ideal IQ) is introduced to study the impact of varying IQ imbalance.

It can be observed in Fig. 4 that the system is more sensitive to IQ imbalance as E_b/N_0 increases. The reason is that when the E_b/N_0 is large, the system is less impacted by the noise and it can maintain high performance. In the absence of IQ imbalance, the BER can reach 10^{-4} when E_b/N_0 = 20 dB. Therefore, even a small imbalance will have a great impact on the system performance in this situation. On the contrary, when E_b/N_0 is small, the thermal noise has a large impact on the system performance and the addition of IQ imbalance will not cause a great difference.

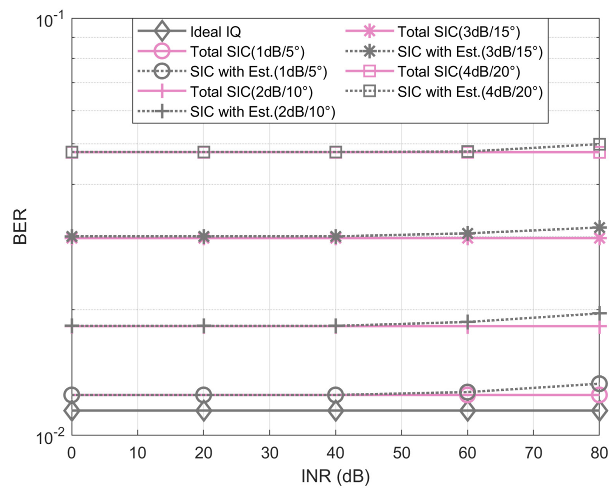


Fig. 5. BER performance with LS estimator compared with total SIC under Eb/No=15 dB. The number of symbols for SI estimation N = 1000

B. BER Performance with Estimation Under IQ Imbalance

The BER performance with the proposed LS estimator under $E_b/N_0 = 15$ dB is shown in Fig. 5. Self-interference-to-noise Ratio (INR) is introduced to measure the strength of the SI signal. The BER performance of the proposed estimator is compared with the total SIC for different IQ imbalance levels. No phase noise is supposed in this case. The BER performance of the FDSM system with total SIC is equivalent to that of the SM system. It can be remarked that even if the INR is high (i.e. the SI and its additional signal which is due to the IQ imbalance are both much larger than the required signal), the system can still maintain the performance at an acceptable level. The simulation results correspond to the theoretical analysis in equation (8).

For comparison, the BER performance with the proposed estimator under INR = 40 dB for the conventional SM system while varying E_b/N_0 and for different levels of IQ imbalance is presented in Fig. 6. The BER performance for the FDSM system while varying E_b/N_0 and for different levels of IQ imbalance is presented in Fig. 7. When comparing the two BER variations, one can remark that the FDSM system as

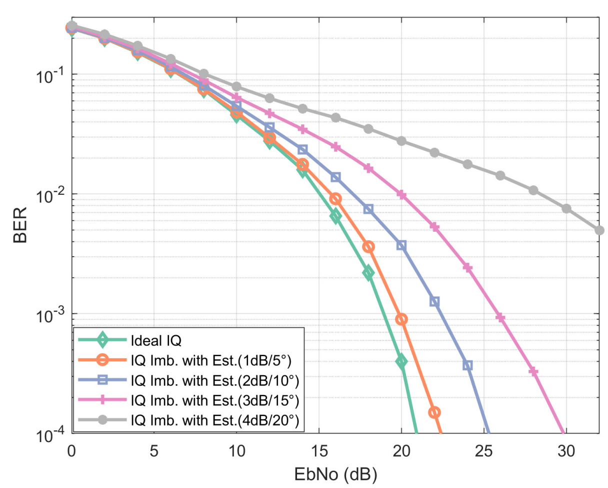


Fig. 6. BER performance of SM system for different IQ imbalance levels

a slightly degraded BER performance, i.e. SIC can reach an

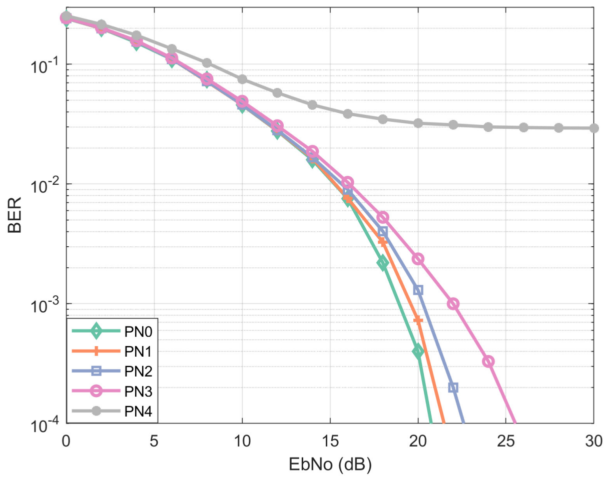


Fig. 7. BER performance of FDSM system with LS estimator for different IQ imbalance levels

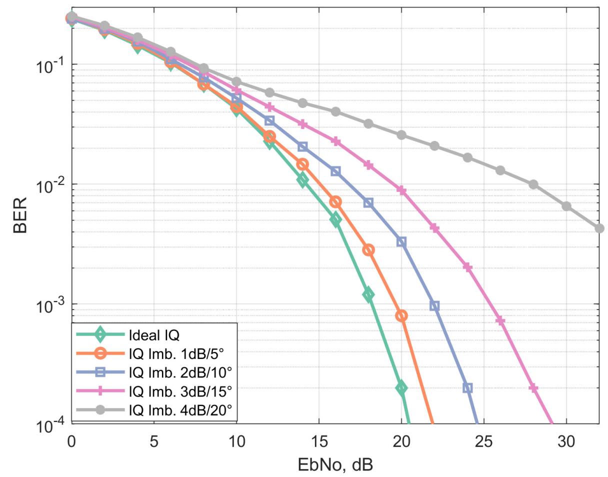


Fig. 8. BER performance of FDSM system under different phase noise levels with ideal IQ

acceptable level.

C. BER Performance Under Different Phase Noise Levels

The phase noise level of the receiver's local oscillator is another factor that can degrade the overall FDSM. In order to study its impact, several phase noise levels are considered (Table II). The PN1 corresponds to the phase noise of the NI PXIe-5644R RF vector signal transceiver (VST), the instrument planned for the measurement campaigns.

TABLE II
DATA OF DIFFERENT PHASE NOISE LEVELS

PN(dBc/Hz) \ Freq.(kHz) Level	0.1	1	10	100	1000
Phase Noise Level 0 (PN0)	No phase noise				
Phase Noise Level 1 (PN1)	-83	-101	-104	-115	-143
Phase Noise Level 2 (PN2)	-63	-81	-84	-95	-123
Phase Noise Level 3 (PN3)	-53	-71	-74	-85	-113
Phase Noise Level 4 (PN4)	-43	-61	-64	-75	-103

The BER performance under different phase noise levels while INR=40 is shown in Fig. 8. The impact of the phase noise on the BER performance is non-linear. The BER can be kept at an acceptable level until PN3, since with PN4, the BER performance significantly degrades.

IV. Conclusion

In this paper, the performance of the FDSM system has been analyzed in presence of the IQ imbalance, of the receiver's local oscillator and of the phase noise. In theory, even though the SI signal is totally cancelled, the residual signal caused by the receiver non-idealities can significantly degrade the system performance. A LS estimator is proposed to suppress the SI signal received by the imperfect RF receiver. We observed that the system is more sensitive to IQ imbalance at low signal-to-noise ratios. The numerical results show that the proposed estimator can reach an acceptable BER consistent with theory. The phase noise of the instrument planned for the measurement campaigns slightly influences the system BER performance. Future work will focus on building an experimental setup to confirm the presented simulation results.

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