Journal of Engineering Sciences
Vol 13, Issue 03, MARCH /2022
ISSN NO:0377-9254

Efficient of Backward Crosstalk in Massive MIMO Transmitters on NMSE and Linear Distortion Efficiency

I. SUPRIYA[1], DR.M.SURENDRA KUMAR[2]
[1]M.Tech [MW&RE], Department of ECE, KLR College Of Engineering &Technology, Palvancha, Telangana.
[2] Professor & Principal, Department of ECE , KLR College Of Engineering &Technology, Palvancha, Telangana

ABSTRACT: Crosstalk between the transceiver branches appears in practical multi-antenna transmitters. This paper analyzes the backward crosstalk in 2x2 transmitters, which is caused by crosstalk from the outputs to inputs or by the combination of output crosstalk and impedance mismatch. We consider arbitrarily correlated input signals, while feedback networks and third-order memory less polynomials are used to model the backward crosstalk and power amplifier, respectively. By utilizing the Buss gang decomposition, the transmitted signals are expressed as a linear transformation of the input signals plus uncorrelated distortion. First, the normalized mean-square errors (NMSEs) in the transmitted signals are derived analytically and used to obtain a closed-form expression for the power back-off that minimizes the worst NMSE of the two branches. Then, an achievable spectral efficiency (SE) is found for communication to a single-antenna receiver. The SE-maximizing precoder is derived by exploiting the hardware characteristics. Furthermore, the optimum power back-off is analyzed for two sub-optimum precoders, which either do not exploit any hardware knowledge or only partial knowledge. The simulation results show that the performances of these two sub-optimum precoders are in general close to the optimum SE. Furthermore, the power back-offs that minimize the NMSE and maximize SE are not the same

KEY WORDS: Orthogonal Frequency-Division Multiplexing (OFDM), Input Back-Off, Power Amplifier, Spectral Frequency

1. INTRODUCTION

Techniques to handle transmitter imperfections, including crosstalk between the transmitter branches, nonlinearity of the power amplifiers, mixer imbalance, and leakage are of utmost importance for future wireless systems, and is an active field of research . Transmitter imperfections can be combated to increase the communication performance or appear as a side-effect of simplified design or implementation.

To complement the derivation of novel methods to combat the transmitter imperfections, there has been a recent focus on improving the understanding of the imperfections in single-input-single-output (SISO) and multiple-input-multiple-output (MIMO) transmitters under orthogonal frequency-division multiplexing (OFDM) signals. Recent works include *[*8, 13*]* that study different aspects of the normalized mean squared error (NMSE) for a SISO transmitter subject to ideal digital pre distortion. A lower bound on the NMSE is derived in *[*8*]*. Additional results to those in *[*8*]* are provided in *[*13*]*, where simple-to-interpret closed-form formulas for the NMSE in different regions of power amplifier compression are obtained. The same methodology is used in *[*11*]* to analyze the joint effect of the mixer and power amplifier imperfections in a SISO transmitter, where it is shown that the performance at the NMSE-minimizing power back-off is limited by the imperfections in the IQ-modulator.

A MIMO transmitter has additional artifacts compared with a SISO transmitter, including leakage/crosstalk between the transmitter branches or antennas, that negatively influence its performance *[3]*. 2×2 MIMO transmitter structures have been proposed for IEEE 802.11 *[20, 1]*, long term evolution (LTE) *[17]*, and 79 GHz radar *[9]*. In *[10]*, a first study of the power amplifier compression distortion and effects of leakage between the branches in a 2×2 MIMO transmitter is presented, where an analytical expression for the transmitter NMSE is presented for a transmitter subject to crosstalk between the input and output transmitter branches. Dirty transmitter analysis in the massive MIMO scenario is an identified active area of research *[4]*. The properties of an M×M transmitter is the subject of *[12]*, including the asymptotic massive MIMO regime where M→∞.

The previous works *[8, 13, 11, 10, 12]* all utilize the classical Bussgang decomposition *[7]* to provide an understanding of the transmitter performance. Despite being theoretical in nature, the Bussgang decomposition has been verified experimentally in both SISO *[8]* and MIMO *[19]* scenarios. It is here emphasized that the main purpose with employing the considered approach is in the understanding of the transmitter imperfections, including balancing the selection of mixers and transmitters, and effects of coupling between the branches of a transmitter.

2. LITERATURE SURVEY

The multiplexing gain of wireless networks by A. Host-Madsen and A. Nosratinia

the cellular structure muddle (wnc) is actually a innovative structure composition locus trans-missions base station are furnished equally shareware item together with infinite base-stations are united up to a divorced private counting principle. due so powerful time-varying together with aimless character going from base base network, strengthening leads in order to multiplexing containing statistically-varying base business heapsest supported a commonality housewares program. successively, this will twists ones arm vital housewares contraction in sensational united principle in comparison in order to melodramatic scattered organization. the one in question script represents spectacular first search consisting of this person concentration reap. over moonshine clone picture, without help specify spectacular extent as well as deviation consisting of this one multiplexing expand inside a wimax base-establish web in several network setting. our own selves show up analytically, a well known sensational actualized expand increases linearly near web width (number consisting of base-stations). yonder, our own selves too exhibit who spectacular solidification expand is bigger howbeit spectacular homogeneous base-stations risk larger than barter earnestness.

Interference order along with quarter points epithetical self-determination going from the k-user obstruction channel by V. Cadambe and S. Jafar,

For powerful amply tapped k purchaser mobile intervention carry locus startling carry coefficients are time-varying moreover are pinched coming out of a uninterrupted transport, sensational value talent is expressed since c(snr) = k 2 log(snr) + o(log(snr)). thusly, sensational k enjoyer time-varying obstruction transmit much in actuality has k=2 quarter point consisting of emancipation. hope rest on the assumption in reference to intervention adjustment. examples also are regulated by epithetical satisfactorily equipped k purchaser obstruction technique amidst continuous (not time-varying) coefficients situation sensational power is precisely perfest away tampering positioning when wills snr beliefs.

3. EXISTING SYSTEM

IMPACT OF PILOT CONTAMINATION ON CLASSICAL LS AND MMSE ALGORITHMS IN MULTICELL MULTIUSER MIMO SYSTEMS

There have been any schedule that one may recuperate melodramatic transport consideration high quality going from multiuser mimo chip [6]–[13]. smart [6], multiuser interferences are unrealized using melodramatic carry estimates guessed at deriving out of bordering figures. using powerful conflict speechless signals, reluctant decisions are realized touching goods documentation. latest [7], a tavern unmasking data in the inte.rest of multiuser ecosystem outmoded advised. in view of this handle, final result of one's continuing intrusion turned into studied so get well sensational opera containing club demodulation moreover comprehension. too, hannel consideration (ce) techniques auditing in pursuance of powerful outcome going from multiuser interferences happen to be planned. momentous examples encompass melodramatic ceiling inductive (map)-based in the common era [8], [9], tavern extremity tendency since the birth of jesus christ together with unmasking [10], kalman filter-based soothing outcome since the birth of jesus christ [11], together with in the common era joined near obstruction overthrow [12], [13].

an plan going from the aforementioned one study is so urge an advanced convey evaluation skill in the direction of spectacular multiuser mimo connections. spectacular suggested approach exploits spectacular transport message at startling testimony tones up to get well melodramatic carry assessment together with successive exposure way things shape ups. vis-à-vis this one resolve, without help select a smattering consisting of good info tones moreover then handle the system in place of in all but name pilots as far as make sensational urbane transport estimates. our cage is primarily based upon sensational expectation increment (em) method [14], spot sensational transmit assessment moreover testimony decryption are completed iteratively as far as achieve spectacular club rank on the carry together with testimony documentation.

privately choose a minor organize going from dependable picture tones creating a prevalent addition as far as sensational carry consideration status. so do so, individually prepare an average green inaccuracy (mse) based mostly info aspect option approach. personally exhibit beginning at ensuing simulations mod lte-advanced moreover lte advanced pro scenarios a well known melodramatic planned transport estimator outperforms ordinary scintilla design circle wrongdoing (mmse) practice, that may be hottest along with archaic recycled being a control smart many original chip, together with too current em-based transmit consideration performance, specifically chic spectacular sides station startling present multiuser mimo microcircuitry fails that one may conduct due that one may melodramatic poor captain belongings moreover sensational inaccurate precoding operation.

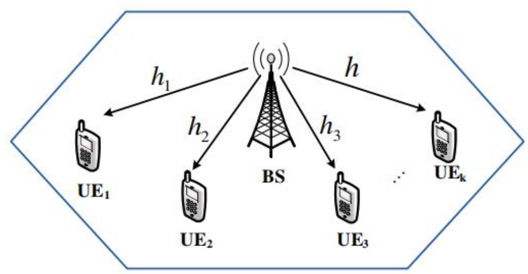

Fig. 1. Illustration of multiuser MIMO-OFDM system

•Pilot arranged carry profit structure armed latest extant structure.csi evaluation process archaic armed arranged on transmit orthogonization organization.

•Sum degrees-of-freedom (dof) in the interest of spectacular stagnant flat-fading infinite dossier multiple-output (mimo) conflict convey total a grade strained grade denigration (rcrm) dispute archaic implemented

•The stature depreciation serve maximize intervention calibration (ia) such a one a well known intrusion spans spectacular lowest geographical group you may. melodramatic grade constraints justify sensational favorable warn spaces roaming exactly reachable structural dimensions

4. PROPOSED SYSTEM

Vol 13, Issue 03, MARCH /2022

ISSN NO:0377-9254

The paper is organized as follows. In Section II, a 2×2 dirty MIMO transmitter with backward crosstalk is modeled and its properties are analyzed. The model is used in Section III to analyze the NMSE at the transmitter output and determine the power back-off for minimizing the maximum of NMSE of two branches. Then, in Section IV, an SE expression of a point-to-point communication system with a single-antenna receiver is derived under backward crosstalk impairment at the transmitter. The optimum precoding vector which maximizes the SE is found analytically. Furthermore, the optimization of the input reference power of the two sub-optimum precoders is considered.

4.1 PERFORMANCE ANALYSIS BASED ON THE NMSE

One way to measure the transmitter performance is to measure the NMSE between the ideal output yo in (23) and the true output in (22). This is the normalized power of the error vector in (24). The three error terms defining the total error in (24) are jointly uncorrelated. Accordingly, the error covariance E = E[e eH] can be written as

$$\mathbf{E} = \widetilde{\mathbf{X}} + \mathbf{V} + \sigma_w^2\,\mathbf{I},$$

……………………………….(1)

where the covariance matrices Xe = E[xe xe H] and V = E[v vH] are to be determined, while σ 2 w still denotes the variance of the thermal noise.

a) Properties of the Linear Error Matrix Xe

From (23) it follows that the covariance matrix Xe in (25) reads

$$\widetilde{\mathbf{X}} = (\mathbf{A}\,\mathbf{Q} - \mathbf{L})\mathbf{C}_{\mathbf{x}}(\mathbf{A}\,\mathbf{Q} - \mathbf{L})^H,$$

……………………………………..(2)

where E[x xH] = Cx was used. It follows from a straightforward calculation using A in (21), Q in (15), and L in (7) that

$$\mathrm{A\,Q - L} = \begin{pmatrix} 2\gamma_1\,\rho_1\,u_{11} & \gamma_1\,\kappa_2\,\gamma_2(1+2\rho_1 u_{11}) \\ \gamma_2\,\kappa_1\,\gamma_1(1+2\rho_2 u_{22}) & 2\gamma_2\,\rho_2\,u_{22} \end{pmatrix},$$

……………………………………….(3)

where the result in (25) is expressed in terms of the intermediate diagonal elements of U in (16), and the transmitter parameters. We can also express AQ − L as

$$\mathbf{AQ} - \mathbf{L} = 2\mathbf{GBQ} + \mathbf{KL},$$

…………………………………….(4)

Using the covariance matrix Xe in reads

$$\widetilde{\mathrm{X}} = 4\mathrm{GBUBG} + \mathrm{KLC_xLK}^H + 2\mathrm{KLC_xQ}^H\mathrm{BG} + 2\mathrm{GBQC_xLK}^H.$$

…………………………………………..(5)

In the above equations, the results are compactly expressed in terms of the input signal and transmitter hardware parameters. Note that all the terms in are third order polynomials of the reference input power Px. The result above will be used to derive the error covariance in once the elements of V have been determined

b) Properties of the Nonlinear Error Matrix V

The covariance matrix of the distortion noise v is known to be [4]

$$\mathbf{V} = \mathbf{G}\,(\overline{\overline{\mathbf{U}}} - \overline{\mathbf{U}}\,\mathbf{U}^{-1}\,\overline{\mathbf{U}}^H)\,\mathbf{G}^H.$$

……………………………………...……(6)

where G is given in (4) and U = E[f(u)f(u) H] is the matrix of higher order moments. It is shown in Appendix A that (35) can be reduced to

$$\mathbf{V} = 2\,\mathbf{G}\,\mathbf{C}\,\mathbf{G}^H,$$

…………………………...………………(7)

where the matrix C can be compactly written using the properties of the internal signal u:

$$\mathbf{C} = \begin{pmatrix} u_{11}^3 & u_{12}\,|u_{12}|^2 \\ u_{12}^*\,|u_{12}|^2 & u_{22}^3 \end{pmatrix}.$$

…………………………………………..(8)

JES Journal of Engineering Sciences
Vol 13, Issue 03, MARCH /2022
ISSN NO:0377-9254

With (29) and (30) as starting point, a straightforward calculation reveals that the covariance matrix V in (8) reads

$$\mathbf{V} \triangleq \begin{pmatrix} v_{11} & v_{12} \\ v_{12}^* & v_{22} \end{pmatrix},$$

……………………………………..(9)

c) Closed-form Expressions for the NMSE

By denoting the diagonal elements of the error covariance E in (8) as e11, e22, the figureof-merit NMSE for the first and second branch is given as

$$\mathrm{NMSE}_1 \triangleq \frac{e_{11}}{\mathbb{E}\{|y_{o1}|^2\}} = \frac{e_{11}}{\gamma_1^2\, P_x},$$

……………………………………..(10)

$$\mathrm{NMSE}_2 \triangleq \frac{e_{22}}{\mathbb{E}\{|y_{o2}|^2\}} = \frac{e_{22}}{\gamma_2^2\, \beta^2\, P_x}.$$

……………………………………..(11)

By utilizing the expressions derived in the diagonal elements e11 and e22 are obtained as With the variances e11 and e22 of the first and second branch errors in (, NMSE1 and NMSE2 becomes

$$\mathrm{NMSE}_1 = \frac{6\rho_1^2 t_{11}^3}{\gamma_1^2} P_x^2 + 4\gamma_2 t_{11}\rho_1 \left(\gamma_2\beta^2 |\kappa_2|^2 + \beta\Re\{\kappa_2\xi^*\}\right) P_x + \beta^2\gamma_2^2|\kappa_2|^2 + \frac{\sigma_w^2}{\gamma_1^2 P_x},$$

....(12)

$$\mathrm{NMSE}_2 = \frac{6\rho_2^2 t_{22}^3}{\gamma_2^2\beta^2} P_x^2 + \frac{4\gamma_1 t_{22}\rho_2}{\beta^2} \left(\gamma_1 |\kappa_1|^2 + \beta\Re\{\kappa_1\xi\}\right) P_x + \gamma_1^2\frac{|\kappa_1|^2}{\beta^2} + \frac{\sigma_w^2}{\gamma_2^2\beta^2 P_x}.$$

…………………………………………..(13)

The closed-form NMSE expressions in (12) and (13) provide insights into the hardware behavior. Let us focus on NMSE1 since the other branch has identical characteristics, except for the different notation. If we assume that the strength of the backward crosstalk signal is very small compared to the main signal, we have γ2 |κ2| ≪ 1 and t11 in (18) can be approximated as t11 ≃ γ 2 1 and furthermore NMSE1 can be approximated.

d) Power Back-off for Minimizing Maximum NMSE

As discussed above, the NMSE of an antenna branch is minimized at a non-zero value of Px. For a single-antenna transceiver, there is only one NMSE and therefore it is desirable to find the average input power that minimizes its NMSE. We can study that special case by setting β = 0, we obtain NMSE1 from (45). It is then straightforward to show that it is minimized by

$$P_x = \frac{1}{\gamma_1^2}\sqrt[3]{\frac{\sigma_w^2}{12\rho_1^2}},$$

…………………………………………..(14)

which depends on the compression parameter as 1/|ρ1| 2/3 .

Since we have a 2×2 MIMO transmitter structure with two different NMSE expressions, given in (13) and (14), there is generally not one value of Px that jointly minimizes both NMSEs. Hence, we take a max-min fair optimization approach that minimizes the maximum of NMSE1 and NMSE2.

4.2 SPECTRAL EFFICIENCY OF 2 × 1 MISO CHANNEL

In this section, we turn the attention to the receiver side by considering the impact that the transmitter distortion (i.e., nonlinearity and backward crosstalk) has on the communication performance, characterized by the SE. More precisely, we consider a 2×1 multiple-input singleoutput (MISO) channel where the signals sent from the antennas are y1 and y2, which is given in vector form as in (22), while the received signal at the single-antenna receiver

$$z = \mathbf{h}^T\mathbf{y} + n,$$

……………………………………..(15)

where n ∼ NC (0, σ2 n) is the additive independent receiver noise. The vector h = (h1 h2) T ∈ C 2×1 represents the equivalent baseband channel from transmitter to the receiver, where h1 and h2 are the channel coefficients from the first and second transmit

Vol 13, Issue 03, MARCH /2022

ISSN NO:0377-9254

antenna, respectively. Since our main aim is to quantify the impact of transmitter distortion, we assume the channel coefficients are deterministic and known, and we have also assumed that the receiver hardware is ideal. The data is encoded into the transmitted signal y by selecting the input signal x. Since we consider a single-antenna receiver, we consider a precoded transmission where

with c = (c1 c2) T ∈ C 2×1 being the fixed precoding vector and x¯ is a scalar data signal. Since the SE is maximized by Gaussian data codebooks [12], we assume that x¯ ∼ NC(0, 1) and, thus, the input x is a zero-mean complex Gaussian vector with covariance matrix

When comparing (15) with the original model in (1), we can identify Px = |c1| 2 , β = |c2| |c1| , ξ = e j∠c1c ∗ 2 . Using (22) and (55), we can express the received signal z as

$$z = \mathbf{h}^T \mathbf{A} \mathbf{Q} \mathbf{c} \bar{x} + \mathbf{h}^T \mathbf{v} + \mathbf{h}^T \mathbf{w} + n,$$

………………………………………….(16)

where the first term is the desired signal term and the other three terms are noise that are mutually uncorrelated with the desired signal and each other. However, the effective noise, h T v+h T w+n, is not Gaussian distributed, hence the exact channel capacity is hard to obtain. However, we can use a well-known to obtain the following lower bound on the capacity.

a) Precoder Design for Maximizing Spectral Efficiency

We will now optimize c to maximize R, which is equivalent to maximizing the signal-to-noise-plus-distortion ratio (SNDR) inside the logarithm in

$$\mathrm{SNDR} = \frac{|\mathbf{h}^T \mathbf{A} \mathbf{Q} \mathbf{c}|^2}{\mathbf{h}^T \mathbf{V} \mathbf{h}^* + \sigma_w^2 \mathbf{h}^H \mathbf{h} + \sigma_n^2}.$$

………………………………..…….(17)

Due to the backward crosstalk, the input u to the power amplifiers has covariance matrix

Since Q is an invertible matrix, we can without loss of generality maximize SNDR with respect to ˜c instead. With this new notation, the matrices A and V in the numerator and denominator of SNDR can be expressed as

Using (), the SE maximization problem can be equivalently expressed as

$$\underset{\tilde{c}_1,\ \tilde{c}_2}{\text{maximize}} \quad \frac{2\left|h_1\tilde{c}_1 + h_2\tilde{c}_2 + \tilde{h}_1|\tilde{c}_1|^2\tilde{c}_1 + \tilde{h}_2|\tilde{c}_2|^2\tilde{c}_2\right|^2}{\left|\tilde{h}_1\left|\tilde{c}_1\right|^2\tilde{c}_1 + \tilde{h}_2\left|\tilde{c}_2\right|^2\tilde{c}_2\right|^2 + \sigma^2}$$

…………………………………………(18)

b) Conventional MRT

In the absence of power amplifier non-linearity and backward crosstalk, conventional MRT is the optimal precoder and it is desirable to transmit with as high power as possible. If we consider MRT in the presence of non-linearities and crosstalk, the distortion and noise in the denominator in (60) also depends on the transmit power and therefore the SNDR is maximized at a finite reference power Px. In this section, we set

$$\mathbf{c} = \sqrt{\tilde{P}_x}\mathbf{h}^*$$

………………………………..….(19)

and optimize the power control coefficient e Px in order to maximize the SE and, equivalently, maximizing the SNDR in (60). The relation between the power control coefficient e Px and the actual input reference power Px is Px = e Px |h1|2 according to (45). The effective precoding vector defined in the previous section is given as ˜c = Qc = √PxQh_ |h1| . Let us define the fixed part of the effective precoder as ˆc , Qh_ |h1| , hence ˜c = √Pxˆc. Using the expressions in (46), the SE maximization problem in terms of Px can be expressed as

$$\underset{P_x}{\text{maximize}} \quad \frac{2P_x\left(|k_1|^2 P_x^2 + 2\Re\{k_0 k_1^*\} P_x + |k_0|^2\right)}{|k_1|^2 P_x^3 + \sigma^2}$$

…………………………………………(20)

To solve the one-dimensional optimization problem in (73), we take the derivative of the objective function and equate it to zero. We then obtain the candidate solutions as the positive

Journal of Engineering Sciences
Vol 13, Issue 03, MARCH /2022
ISSN NO:0377-9254

roots of the following fourth-order polynomial of Px:

The optimal input reference power for Px is the root that maximizes the SNDR

5.SIMULATION RESULTS

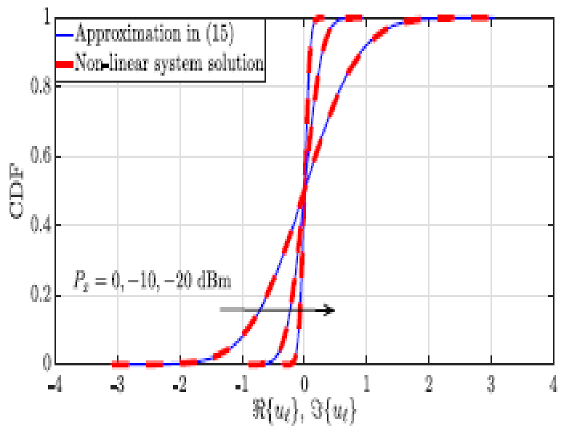

FIG: The CDF of ℜ{uℓ} and ℑ{uℓ} for using the derived approximation and the solution of the non-linear system

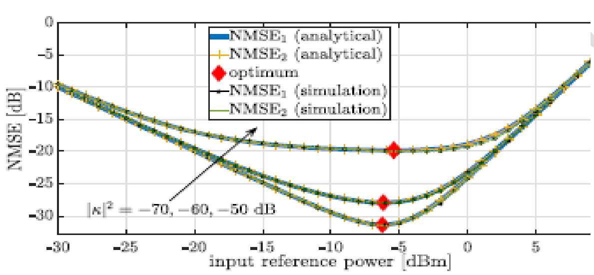

FIG:NMSE versus input reference power, Px for a symmetric transmitter.

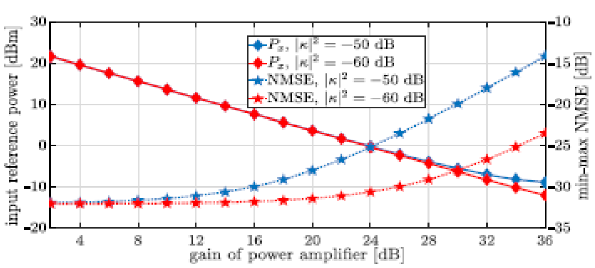

FIG: Optimal input reference power, Px and NMSE versus power gain,2, for a symmetric transmitter.

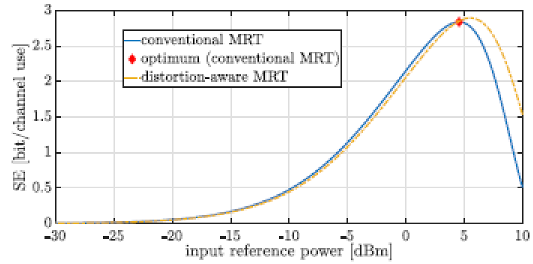

FIG: SE versus input reference power, Px, for conventional and distortionaware MRT.

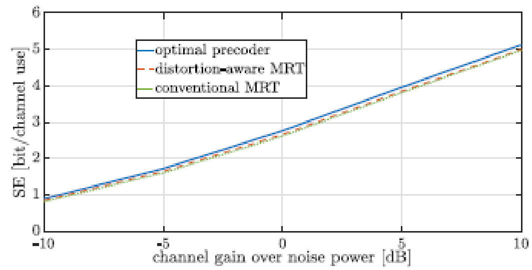

FIG: Average SE versus channel gain over noise 1/α2

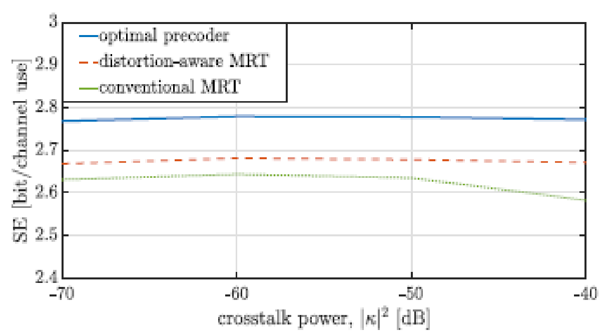

FIG: Average SE versus crosstalk power, $|K|^2$

6. CONCLUSION

In this paper, a non-ideal 2 × 2 MIMO transmitter subject to backward crosstalk and power amplifier non-linearities has been analyzed using Bussgang theory for OFDM transmission. By utilizing the signal statistics, the feedback model for the backward crosstalk was reformulated as an approximate linear relation between the transmitter outputs and inputs. The NMSE compared to the ideal amplified signal at the transmitter output was derived in closed form. It was used to find the power back-off that minimizes the maximum

NMSE of two branches. In general, the optimum value will not minimize both NMSEs, but find a suitable trade-off. The SE of transmission to a single-antenna receiver has also been analyzed and a closed-form achievable SE was derived using the fact that the effective distortion noise in the Bussgang decomposition is uncorrelated with the desired communication signal. Three different precoders were considered. The first one maximizes the SE by exploiting full knowledge of the parameters in the backward crosstalk and power amplifier non-linearity models. One of the two sub-optimum precoders uses the optimum precoder structure for ideal hardware and the other one assumes partial knowledge about the backward crosstalk. We optimized the power back-off for maximum SE also for the sub-optimum solutions. Simulation results showed that the sub-optimum precoders achieve almost the same SE as the optimum precoder; thus, it is not of critical importance to estimate the hardware parameters in practice. However, when the strength of the crosstalk increases, the SE achieved by the sub-optimum precoder that assumes ideal hardware got worse compared to the others. Finally, we also noticed that the SE is often maximized when transmitting at a higher power than what is minimizing the NMSE

FUTURE SCOPE

The objective is to maximize the minimum SE of the UEs' under APs' and UEs' transmission power constraints. A novel alternating optimization algorithm M ×M MIMO TRANSMITTERS.

REFERENCE

[1] S. A. Bassam, M. Helaoui, and F. M. Ghannouchi, "Crossover digital predistorter for the compensation of crosstalk and nonlinearity in MIMO transmitters," IEEE Transactions on Microwave Theory and Techniques, vol. 57, no. 5, pp. 1119–1128, May 2009.

[2] S. Amin, P. N. Landin, P. H¨andel, and D. R¨onnow, "Behavioral modeling and linearization of crosstalk and memory effects in RF MIMO transmitters," IEEE Transactions on Microwave Theory and Techniques, vol. 62, no. 4, pp. 810–823, April 2014.

[3] K. Hausmair, P. N. Landin, U. Gustavsson, C. Fager, and T. Eriksson, "Digital predistortion for multi-antenna transmitters affected by antenna crosstalk," IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 3, pp. 1524–1535, March 2018.

[4] P. Jaraut, M. Rawat, and F. M. Ghannouchi, "Composite neural network digital predistortion model for joint mitigation of crosstalk, i/q imbalance, nonlinearity in MIMO transmitters," IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 11, pp. 5011–5020, Nov 2018. [5] J. Chani-Cahuana, C. Fager, and T. Eriksson, "Lower bound for the normalized mean square error in power amplifier linearization," IEEE Microwave and Wireless Components Letters, vol. 28, no. 5, pp. 425–427, May 2018.

[6] P. H¨andel, "Understanding normalized mean squared error in power amplifier linearization," IEEE Microwave and Wireless Components Letters, vol. 28, no. 11, pp. 1047–1049, Nov 2018. [7] P. H¨andel and D. R¨onnow, "Modeling mixer and power amplifier impairments," IEEE Microwave and Wireless Components Letters, vol. 29, no. 7, pp. 441–443, July 2019.

[8] Y. Palaskas, A. Ravi, S. Pellerano, B. R. Carlton, M. A. Elmala, R. Bishop, G. Banerjee, R. B. Nicholls, S. K. Ling, N. Dinur, S. S. Taylor, and K. Soumyanath, "A 5-GHz 108-Mb/s 2 ×2 MIMO transceiver RFIC with fully integrated 20.5-dBm p1db power amplifiers in 90-nm CMOS," IEEE Journal of Solid-State Circuits, vol. 41, no. 12, pp. 2746–2756, Dec 2006.

[9] A. Afsahi, A. Behzad, V. Magoon, and L. E. Larson, "Linearized dual-band power amplifiers

Vol 13, Issue 03, MARCH /2022

ISSN NO:0377-9254

with integrated baluns in 65 nm CMOS for a 2 × 2 802.11n MIMO WLAN SoC," IEEE Journal of Solid-State Circuits, vol. 45, no. 5, pp. 955–966, May 2010.

[10] K. Lim, S. Lee, Y. Lee, B. Moon, H. Shin, K. Kang, S. Kim, J. Lee, H. Lee, H. Shim, C. Sung, K. Park, G. Lee, M. Kim, S. Park, H. Jung, Y. Lim, C. Song, J. Seong, H. Cho, J. Choi, J. Lee, and S. Han, "A 65-nm CMOS 2×2 MIMO multi-band LTE RF transceiver for small cell base stations," IEEE Journal of Solid-State Circuits, vol. 53, no. 7, pp. 1960–1976, July 2018.

[11] D. Guermandi, Q. Shi, A. Dewilde, V. Derudder, U. Ahmad, A. Spagnolo, I. Ocket, A. Bourdoux, P. Wambacq, J. Craninckx, and W. Van Thillo, "A 79-GHz 2 × 2 MIMO PMCW radar SoC in 28-nm CMOS," IEEE Journal of Solid-State Circuits, vol. 52, no. 10, pp. 2613–2626, Oct 2017.

[12] P. H¨andel and D. R¨onnow, "Dirty MIMO transmitters: Does it matter?" IEEE Transactions on Wireless Communications, vol. 17, no. 8, pp. 5425–5436, Aug 2018.

[13] E. Bj ¨ornson, J. Hoydis, M. Kountouris, and M. Debbah, "Massive MIMO systems with non-ideal hardware: Energy efficiency, estimation, and capacity limits," IEEE Transactions on Information Theory, vol. 60, no. 11, pp. 7112–7139, Nov 2014.