Compensation of nonlinear distortion in hybrid beamforming MIMO transmitters

Tamara Muškatirović-Zekić [1,2], Milan Čabarkapa [1], Nataša Nešković [1] and Đurađ Budimir [1,3]

[1] School of Electrical Engineering, University of Belgrade, Belgrade, Serbia
[2] Regulatory Agency for Electronic Communications and Postal Services, Belgrade, Serbia
[3] Wireless Communications Research Group, University of Westminster, London, U.K.
E-mail address: muskatirovic@gmail.com, milan.cabarkapa@gmail.com, natasha@etf.rs, d.budimir@etf.rs

Abstract— **Compensation of nonlinear distortion in hybrid beamforming MIMO transmitters is an open and challenging field of research. The goal of the study is to find an efficient method for linearization of power amplifiers in fully connected hybrid beamforming MIMO transmitters, which would not additionally increase the complexity of the system too much. In this paper, the polynomial-based compensation method of nonlinear distortion in hybrid beamforming MIMO transmitters is presented. The method is verified through comprehensive Matlab simulations. A 64x64 fully connected hybrid beamforming MIMO system with 2 RF branches on the transmitting side and 2 RF branches on the receiving side was considered. The proposed memory polynomial digital predistortion model is based on direct transmit-end feedback. Simulations were performed for different parameters of the memory polynomial model and analyzed. The obtained results are presented in graphical form, using Power Spectrum Density, and in numerical form, using metrics in time and frequency domain, such as Normalized Mean-Squared Error and Error Vector Magnitude. It is shown that the proposed memory polynomial digital predistortion model can very well compensate nonlinear distortion in fully connected hybrid beamforming MIMO transmitter. It has been also demonstrated that with increasing model complexity, ie with increasing memory depth and nonlinearity order of memory polynomial model, better compensation of nonlinear distortion in hybrid beamforming MIMO transmitters can be achieved.**

Keywords- hybrid beamforming (HBF); massive MIMO; DPD; PA; memory polinomial

I. INTRODUCTION

MIMO (multiple-input multiple-output) transmitters are one of the most widespread solutions for increasing bandwidth and spectral efficiency in new generation mobile systems. Due to the complexity of the hardware and high-power consumption, the application of conventional digital beamforming in mMIMO (massive MIMO) transmitters is impractical. Therefore, the technique of hybrid beamforming for mMIMO systems has been proposed in the literature, in which beamforming is divided into analog and digital beamforming [1] - [2]. Analog beamforming is performed in the RF domain, and digital beamforming is performed in baseband. The use of hybrid beamforming reduces the number of phase shifters, RF chains and other expensive components, such as mixers and ADC/DAC converters, thus reducing power consumption and hardware complexity.

As the transmitters of the new generation mobile systems are expected to work with as little power as possible and to be as energy efficient as possible, special attention should be paid to the energy efficiency of the power amplifiers (PA) in the mMIMO transmitter. Therefore, very nonlinear power amplifiers that work in the area close to saturation are used, and they need to be linearized as efficiently as possible. In order to maintain linearity and improve the efficiency of the power amplifier, various DPD (Digital PreDistortion) systems are used.

The basic principle of the DPD system is that for each power amplifier there is a separate DPD block which reduces the nonlinear distortion it introduces. This is not feasible with mMIMO transmitters, so in the literature special attention has been paid to the optimization and simplification of digital signal predistortion. In [3], an overview of existing solutions for digital predistortion of hybrid beamforming MIMO transmitters with partially connected HBF (hybrid beamforming) architecture is given. The considered DPD models are based on feedback directly from the transmission end.

The decorrelation DPD model uses a combined signal of output from individual PAs in conjunction with a decorrelation-based learning rule. CL (closed loop) DPD is a Multiuser Hybrid MIMO solution that uses a single DPD block per RF transmission chain. The BO-DPD (Beam-Oriented DPD) model linearizes the signal of the main beam, not each PA individually, using the outputs of all PAs to obtain the feedback signal. PSBO-DPD (Power Scalable Beam-Oriented DPD) models and linearizes the signal of the main beam of a given chain using feedback from only one PA. As a fully connected HBF architecture allows higher spectral efficiency compared to a partially connected HBF architecture, the authors in [4] proposed a model for linearization of a fully connected HBF mMIMO transmitter. The proposed model consists of several DPD blocks based on the MP (Memory Polynomial) model, one in each of the *P* RF transmitter chains.

In this paper, the MP DPD model for a fully connected HBF architecture based on feedback directly from the end of the transmission is considered, using one DPD block to linearize all amplifiers in the transmitter. Since only one DPD block is used for linearization, this configuration is a less complex solution compared to the solutions proposed in the existing literature.

A description of the proposed DPD model is given in Chapter II, the simulation results are presented in Chapter III, while a conclusion is given in Chapter IV.

II. DPD MODEL FOR HBF MIMO TRANSMITTER

A. HBF transmitter architecture

In HBF transmitters, N_S data strings are converted in a digital transcoder into input signals for *P* RF chains, which are then converted in an analog precoder into signals sent to N_T antenna elements. Depending on the method of implementation of hybrid beamforming in the RF domain, two types of HBF MIMO transmitter architectures are distinguished: a) fully connected and b) partially connected architecture. Fig. 1 shows these two basic types of HBF transmitter architecture.

In a fully connected HBF architecture, each antenna is connected to each of the *P* RF chains, while in a partially connected HBF architecture, a set of *L* antennas is connected to one RF chain. The advantage of a fully connected architecture is that it allows higher spectral efficiency compared to the partially integrated architecture of HBF transmitters.

B. DPD model

Mathematically, the basic principle of hybrid beamforming is the division of the coefficients for signal precoding into coefficients in the baseband (F_{BB}) and coefficients in the RF domain (F_{RF}). The problem of determining the coefficients is a very complex topic and there are a large number of different algorithms in the literature. In this paper the Spatially Sparse Precoding algorithm that searches for orthogonal matching pursuit [5], is used, and the possibility of using a single DPD block to linearize a fully integrated HBF architecture, is analyzed. The block diagram of the model is shown in Fig. 2.
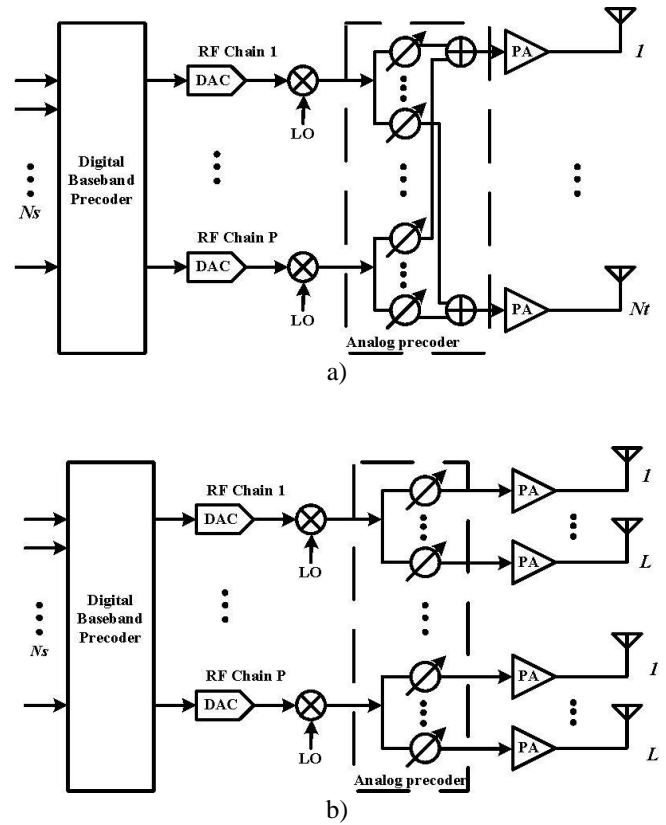

a)

b)

Figure 1.   HBF transmitter architecture: a) fully connected; b) partially connected.

The outputs of each individual PA are led to an anti-beamforming and combining module. The role of this module is to cancel the effect of the beamforming coefficients in the analog beamforming module so that the observed signal in the return RX branch corresponds to the signal that the user needs to receive. The resulting signal is then led to a module to determine the DPD model coefficients. The MP DPD model was used, the use of which is widespread for behavior modeling and digital predistortion of power amplifiers that show memory effects. The output of the MP DPD model is calculated according to the following formula [6]:

$$x_{out}(n) = \sum_{m=0}^{M} \sum_{k=1}^{K} a_{mk} \cdot x_{in}(n-m) \cdot |x_{in}(n-m)|^{k-1} \tag{1}$$

where: a_{mk} - model coefficients, M - memory depth, K - nonlinearity order, x_{in} and x_{out} - input and output signal, respectively.

The proposed MP DPD model was tested through simulations in the Matlab software package.

To evaluate the performance of the proposed DPD model, the following time domain metrics were used Normalized Mean-Squared Error and EVM (Error Vector Magnitude) [7].
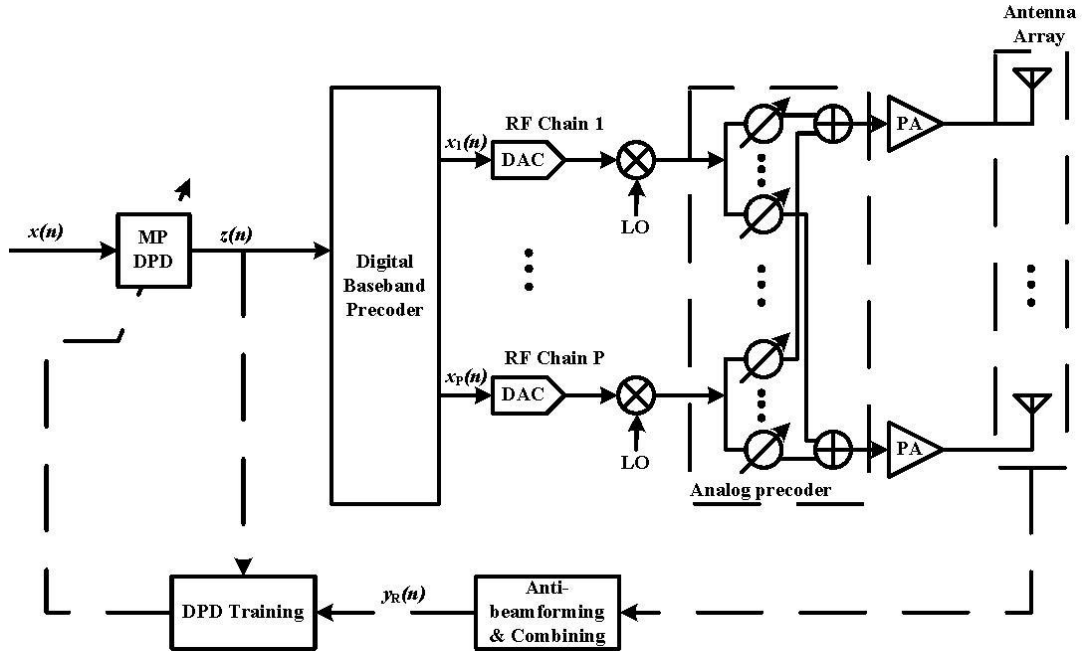
Figure 2.   Block diagram of MP DPD system for HBF MIMO transmitter.

NMSE is calculated using the following formula:

$$NMSE = 10\log_{10}\left(\frac{\sum_{n=1}^{K}|y_{meas}(n) - y_{est}(n)|^2}{\sum_{n=1}^{K}|y_{meas}(n)|^2}\right) \quad (2)$$

where: y_{meas} and y_{est} - measured and estimated waveforms of the output signal, respectively.

While EVM is calculated using the following formula:

$$EVM_\% = \sqrt{P_{error}/P_{ideal}} * 100\% \quad (3)$$

where: P_{error} and P_{ideal} - the error signal power and the reference power of the ideal signal constellation, respectively.

The complexity of the model is determined by the number of coefficients and the number of FLOPs (floating point operations), and are calculated according to the following formulas [8]:

$$N_{coef} = (M + 1)K \quad (4)$$

$$FLOPs = (10 + 2(K - 1)) + (8K(M + 1) - 2) \quad (5)$$

where: *M* - memory depth, *K* - nonlinearity order.

III.   RESULTS

For the purposes of simulations, a 20 MHz OFDM signal was generated, with a subcarrier distance of 15kHz and the number of subcarriers used to be 1200. A real two-stage power amplifier model was used - CFH 2162-P3 PA, with 14 dB gain and P_{1dB}=37 dBm. HBF MIMO transmitter with one input and one output, the so-called single user case, and an MP digital precoder was generated for the entire HBF MIMO transmitter (Fig. 2). A simulation was performed for a 64x64 MIMO HBF system with 2 RF branches on the transmitting side and 2 RF branches on the receiving side. The Saleh-Valenzuela channel model was used, with parameters *Ncl*=6 (number of clusters) and *Nray*=5 (number of rays in each cluster). The parameters selected in this way model the channel in accordance with the 3GPP specification [9].

Simulations were performed for different parameters of the MP model, ie. for different values of memory depth *M* and order of nonlinearity *K*. Taking into consideration the models analyzed in the literature [3] - [4], the following values were chosen for the parameters of the model presented in this paper: 1) M = 2, K = 5; 2) M = 3, K = 7; and 3) M = 3, K = 11.

Fig. 3-6 shows Power Spectrum Density PSD without DPD and using the proposed MP DPD model, for different values of memory depth and nonlinearity, while Table 1 shows the obtained values for EVM and NMSE, as well as values for number of coefficients and FLOPs.

Based on the obtained results, it can be concluded that the proposed MP DPD model very well compensates nonlinear distortion in HBF MIMO transmitters. As the memory depth *M* and the order of nonlinearity *K* increase, better nonlinear distortion compensation is achieved, but at the same time, the computational complexity of the model increases.
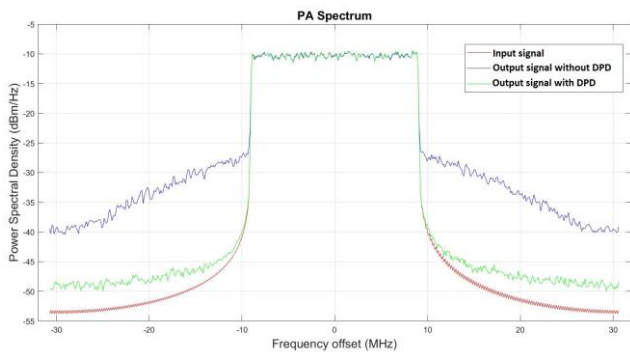
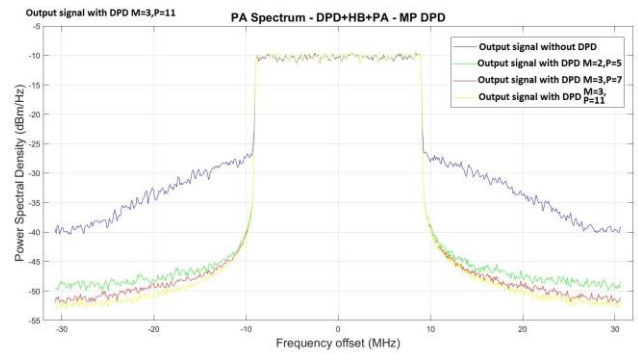Figure 5.   Power Spectrum Density with and without DPD; M=2, K=5.

Figure 6.   Comparative representation of power spectral densities with and without DPD for different values M and K.
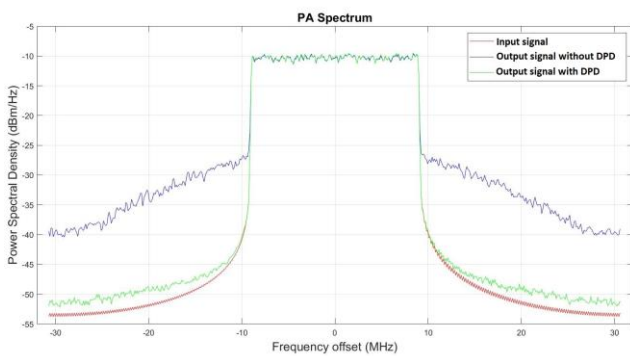

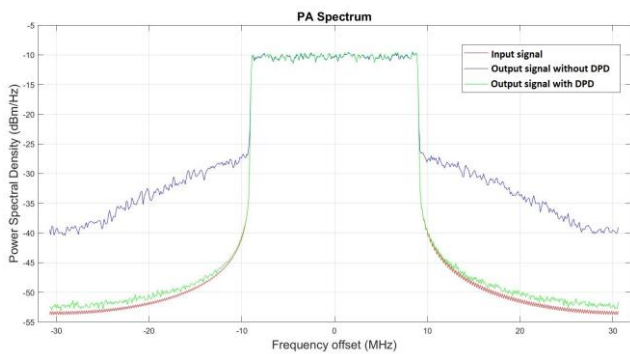Figure 4.   Power Spectrum Density with and without DPD; M=3, K=7.

TABLE I. COMPARISON OF MP DPD MODEL FOR HBF MIMO

Parameters	EVM [%]	NMSE [dB]	N_{coef}	FLOPs
M=2, K=5	2.4179	-32.3312	15	136
M=3, K=7	1.9600	-34.1551	28	244
M=3, K=11	1.7111	-35.3345	44	380

IV.   CONCLUSION

Based on the above, it can be concluded that the use of MP DPD models can very well compensate for nonlinear distortion in hybrid beamforming MIMO transmitters. This paper represents a good starting point for further development of more efficient and less complex models of digital predistortion for transmitters of future broadband mobile systems. It should be noted that this paper discusses the direct transmit-end DPD model. Significant savings in hardware resources can be achieved by using the OTA (over-the-air) DPD model, which does not require feedback from all power amplifiers. On the other hand, the OTA DPD technique requires the installation of an additional antenna in the far field for signal collection and analysis. Future work is aimed at testing digital predistortion in OTA DPD models and finding the optimal DPD model that will most effectively reduce the impact of nonlinear distortion in HBF mMIMO systems.

Figure 3.   Power Spectrum Density with and without DPD; M=3, K=11.

By proposing a DPD system for a fully connected HBF MIMO transmitter architecture that includes a DPD block in each RF transmitter chain, the authors in [4] achieved slightly better results in terms of HBF transmitter linearization (M = 2, K = 5, N_{coef}=112, NMSE = -37dB). Of course, it should be borne in mind that the DPD model from [4] is much more complex than the DPD model proposed in this paper, which, with a much simpler implementation, very well compensates the nonlinearity of HBF MIMO transmitters.

Examining the influence of memory depth and nonlinearity on model complexity and efficiency of nonlinear distortion compensation in hybrid beamforming MIMO transmitters, as well as finding optimal values, presents a new challenge and creates an opportunity for further research in this field.

REFERENCES

[1]   G A. F. Molisch et al., "Hybrid Beamforming for Massive MIMO: A Survey," in IEEE Communications Magazine, vol. 55, no. 9, pp. 134-141, Sepember 2017.

[2]   A. Singh, and S. Joshi, " A Survey on Hybrid Beamforming in MmWave Massive MIMO System," in Journal of Scientific Research, vol. 65, no. 1, pp. 201-213, January 2021.

[3]   Tamara Muškatirović-Zekić, Milan Čabarkapa, Nataša Nešković i Đurađ Budimir, " Pregled rešenja digitalne predistorzije za hybrid beamforming MIMO predajnike " 29. Telecommunication Forum (TELFOR) 2021, November 2021.

[4]   X. Liu, W. Chen, J. Chu, F. M. Ghannouchi and Z. Feng, "Multi-Stream Spatial Digital Predistortion for Fully-Connected Hybrid Beamforming Massive MIMO Transmitters," in IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 68, no. 7, pp. 2998-3011, July 2021.

[5]   O. E. Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi and R. W. Heath, "Spatially Sparse Precoding in Millimeter Wave MIMO Systems," in IEEE Transactions on Wireless Communications, vol. 13, no. 3, pp. 1499-1513, March 2014.

[6] F. M. Ghannouchi, and O. Hammi, „Behavioral modeling and predistortion", IEEE Microwave Magazine, vol.10, no.7, pp.52-64, Dec. 2009.

[7] O. Hammi, M. Younes, and F. M. Ghannouchi, "Metrics and Methods for Benchmarking of RF Transmitter Behavioral Models With Application to the Development of a Hybrid Memory Polynomial Model," IEEE Trans. Broad., vol. 56, no. 3, Sept. 2010.

[8] Pooria Varahram, John Dooley, Keith Finnerty, and Ronan Farrell, " A low complexity pre-distortion scheme for power amplifier linearization in wideband applications", International Journal of Communication Systems, August 2016.

[9] 3GPP Technical Report 38.901, "Study on channel model for frequencies from 0.5 to 100 GHz," v16.1.0 (Release 16), December 2019.

Tamara Lj. Muškatirović-Zekić received the BSc and MSc degrees in telecommunication engineering at University of Belgrade, Serbia, in 2006. She is currently pursuing the PhD degree with the University of Belgrade, Serbia.

In March 2006, she joined the Regulatory Agency for Electronic Communications and Postal Services (RATEL), Serbia, where she is currently a senior advisor for fixed and satellite radiocommunications. Her current research includes behavioral modeling and digital predistortion of RF power amplifiers and linearization of MIMO systems.

Dr. Milan Čabarkapa received BSc and MSc degrees in Electrical Engineering and Computer Science from School of Electrical Engineering, University of Belgrade, Serbia in 2009 and 2010 respectively, and PhD degree in Electronics and Computer Science from Faculty of Science and Technology, University of Westminster, London, UK in 2014.

He is now a research assistant professor as well as a teaching assistant at School of Electrical Engineering, University of Belgrade. His research interests are software modeling, design and development with the focus on cybersecurity and privacy protection as well as design of next-generation communications systems based on 4G, 5G and IoT.

Nataša J. Nešković was born in Kraljevo, Serbia, 1969. She earned her MSc and PhD degrees at University of Belgrade, Serbia, in 1997, and 2003, respectively.

In August 1994, she joined the School of Electrical Engineering, University of Belgrade, Serbia, where she is currently a Full Professor. Her research is focused on the radio network design (radio-access and core network), investigation and modeling of mobile radio channel, development of methods for mobile users positioning, assessment of non-ionising radiation, development of predistortion technique for RF power amplifiers, etc. She is the author of 2 books and has published a number of scientific, journal and conference papers. During the last 28 years, she has been fully involved in several hundreds of projects including design of public (GSM, UMTS, CDMA2000, LTE) and private (TETRA) mobile radio systems as well as in designing of FM radio and TV broadcasting systems. These projects have been mainly conducted by major national telecommunication and power supply companies.

Đurađ Budimir received the Dipl. Ing. and MSc degrees in electronic engineering from the University of Belgrade, Belgrade, Serbia, and the Ph.D. degree in electronic and electrical engineering from the University of Leeds, Leeds, U.K.

In March l994, he joined the Department of Electronic and Electrical Engineering at Kings College London, University of London, UK. Since January 1997, he has been with the School of Computer Science and Engineering, University of Westminster, London, UK, where he is now a Reader of wireless communications. Dr. Budimir is Head of the Wireless Communications Research Group at UoW and a Visiting Professor at the University of Belgrade. He has published more than 350 papers in refereed journals and conference proceedings, four books/book chapters and software's (the book Generalized Filter Design by Computer Optimization, ISBN 0-89006-579-9, Atrtech House Books, March 1998, and the Software and User's Manual EPFIL-Waveguide E-plane Filter Design (Artech House, 2000) and a book chapter in Encyclopedia of RF and Microwave Engineering (Wiley, 2005) over 16 Invited papers/lectures, over 19 Seminars/Workshops, one TV program (BBC World Service programme on Microwaves, 17 Nov. 2010) in the field of RF/microwave and mmWave wireless systems and technologies.