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Linearization of M-LINC Systems Using GMP and Particle Swarm Optimization for Wireless Communications

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ABSTRACT: In this paper, an efficient algorithm for the efficiency maximization of the multilevel linear amplification using nonlinear components (M-LINC) systems is proposed regarding the linearity of the system. In this algorithm, we use the generalized memory polynomial (GMP) to provide a behavioral model for the power amplifier (PA) and calculate the power spectral density (PSD) of the output signal of the system instead of using complicated analytical methods or time-consuming circuit level simulations. In order to have a reliable model, a modeling process which validates the static and dynamic behaviors of the obtained model is provided, and the validation is performed through the time domain signals, PSD, and AM-AM characteristics. As an example, we optimize the efficiency of a 6 level LINC system with a 2.4 GHz 25 W Doherty PA and a 15 MHz three-tone signal using the particle swarm optimization (PSO) method where an upper bound on the adjacent channel leakage ratio (ACLR) is considered as the linearity constraint. Our results show that for each given ACLR limit by a communication standard, the efficiency can be maximized with a certain number of levels in M-LINC system. Furthermore, the results unveil the trade-off between linearity and efficiency in M-LINC systems.

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1. Introduction

In emerging high data rate wireless communication systems like 5G, the linearity and efficiency of the power amplifiers (PAs) have a significant impact on the spectral efficiency and energy efficiency of the system [1, 2]. Conventionally, the maximum efficiency of PAs is near their saturating point where the PA is highly nonlinear. By backing off from the saturating point, the PA will work more linear, however, less efficient. Overcoming this trade-off is a challenging problem in the design of wireless communication systems. Researchers have proposed many linearization techniques to have PAs which are more linear, even near their saturating points [3]. The linear amplification using nonlinear components (LINC) also known as outphasing, tries to linearize the PAs by separating the input signal into constant envelope signals, passing them through the nonlinear PAs and then combining them to have a linearly amplified version of the input signal [4, 5]. A significant problem in the LINC systems is that for a signal with high peak to average power ratio (PAPR), most of the RF power is dissipated in the combiner and so the efficiency of the system is dramatically decreased by this fact. The concept of multilevel LINC (M-LINC) is proposed to reduce the wasted power in the combining process and increase the efficiency of the LINC systems. In an M-LINC system, the input signals to the PAs are not constant envelope, and their envelope can take some distinct values where these values are the system's design parameters [6]. In most of the M-LINC research papers, for a given signal's amplitude probability density function (PDF), the level values are determined in order to maximize the overall efficiency of the system [6, 7].

In an M-LINC system, the bandwidth of the input signals to the PAs is much wider than the bandwidth of the original signal [8, 9]. This phenomenon can violate the linearity of the M-LINC systems due to the limited bandwidth of the PAs of the system [10]. Although in the previous works, the levels of the M-LINC systems are determined through the maximization of the system efficiency regardless of the required system linearity, in this work, we consider the linearity constraints in the design of the M-LINC system. Our goal is to present a method that maximizes the efficiency of the M-LINC system regarding the required linearity constraint. To this aim, we propose the use of generalized memory polynomial (GMP) to calculate the power spectral density (PSD) of the output of the system instead of complicated analytical methods or time-consuming circuit level simulations. We provide a modeling process which models the PA with GMP and also strictly validates the obtained model. Using the obtained model, the efficiency of the system is maximized under the adjacent channel leakage ratio (ACLR) constraints using the particle swarm optimization (PSO) method. The results show that there is a trade-off between linearity and efficiency of the system.

This paper is organized as follows. In Section 2, we provide

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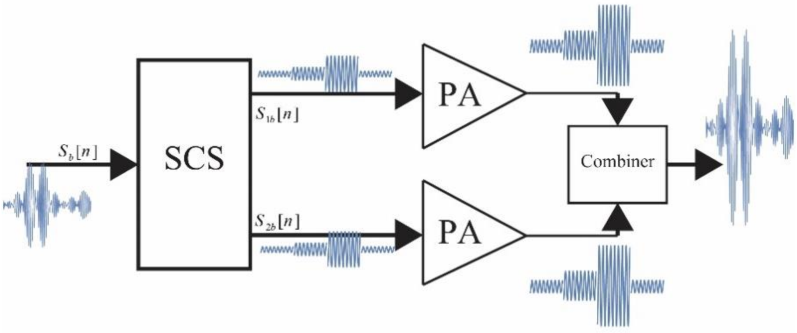


Fig. 1 M-LINC system model.

a detailed system model, including M-LINC system and the GMP model. The modeling process of the PAs is discussed in Section 3. In Section 4, the optimization of the system is performed. Section 5 is the conclusion of this paper.

2. System Model

In this section, we explain the M-LINC system model and the behavioral PA model which will be used in this paper.

2-1- M-LINC system

The considered M-LINC system is shown in Fig. 1. $S_b[n]=r[n]e^{j\theta[n]}$ is the input baseband signal which must be amplified through the M-LINC system where $r[n]$ and $\theta[n]$ are real-valued amplitude and phase of the input signal, respectively. We assume $r[n]\le A_{\max}$ and $f_R(r)$ is the PDF of the amplitude of the input signal $r[n]$. The signal component separator (SCS) generates the baseband signals $S_{1b}[n]$ and $S_{2b}[n]$ such that $S_b[n]=S_{1b}[n]+S_{2b}[n]$ where

$$S_{1b}[n]=\frac{1}{2}a_k e^{j(\theta[n]+\phi[n])}$$
$$S_{2b}[n]=\frac{1}{2}a_k e^{j(\theta[n]-\phi[n])} \tag{1}$$

$$\phi[n]=\cos^{-1}(\frac{r[n]}{a_k}) \tag{2}$$

and a_k is determined from the set of levels

$$A=\{a_k \mid k=0,\dots,N,a_0= A_{\max},a_N=0,\forall k: a_k\ge a_{k+1}\} \tag{3}$$

such that $a_k\ge r[n]\ge a_{k+1}$ and N denotes the number of levels.

Assuming $\eta(p)$ is the efficiency of the PA for the input signal power level to the PA $p=|S_{1b}[n]|^2$, the efficiency of the M-LINC system can be written as [10]

$$Efficiency=\frac{\int_{a_N}^{a_0} r^2 f_R(r)dr}{\sum_{k=0}^{N-1}\frac{a_k^2}{\eta(a_k^2)}\int_{a_{k+1}}^{a_k} f_R(r)dr} \tag{4}$$

2-2- GMP Model

As discussed before, the envelope of the input signal to the PAs is not constant in the multilevel outphasing system, and as a result, the final performance of the system is not ideally linear. On the other hand, by increasing the number of system levels, the efficiency increases; hence, there is a trade-off between linearity and efficiency of the system. Most of the communication standards, to determine the amount of linearity of the PAs, impose some constraints on the PSD at the output of the PAs. In the multilevel outphasing system, to investigate the effect of the selected levels on the PSD of the PA output, analytical methods or simulation techniques can be used. To the authors' knowledge, the analytical methods for deriving the PA output PSD are very complicated and so far have been performed only for the memoryless polynomial models [11, 12]. Moreover, the Circuit Envelope (CE) method, which is used in the simulation of nonlinear circuits with the modulated input signal, by increasing the circuit complexity and input signal bandwidth (decreasing the time steps) becomes very time consuming and may exhibit divergence [13]. The memoryless and memory polynomial models are suitable techniques to model nonlinear systems without and with memory effects, respectively, and these models are well suited for digital pre-distortion (DPD) methods [14]. Here, we adopt the generalized memory polynomial (GMP) for modeling the PA and optimization of the outphasing levels. The output of the GMP model at time index n is the sum of the input signal samples at time index n and $Q-1$ previous ones, i.e., $x[n-q], q\in 0,\dots,Q-1$, which are scaled by the model coefficients and powers of the envelope of their $G-1$ leading and/or lagging input signal samples [15], [16]. In the GMP model, considering the model causality, the input-output relation is given by

$$y[n]=\sum_{p=0}^{P-1}\sum_{q=0}^{Q-1}\sum_{g=0}^{G-1} b_{p,q,g}\,x[n-q]\left|x[n-q-g]\right|^p \tag{5}$$

where $x[n]$ and $y[n]$ are the baseband samples of the input and output signals to the PA at the time instant n, respectively, and coefficients $b_{p,q,g}$ have to be estimated with respect to the nonlinear PA behavior [15]. In this paper, we use the GMP to model a PA, deploy the derived model to obtain the output PSD of that PA, and finally, maximize the M-LINC system

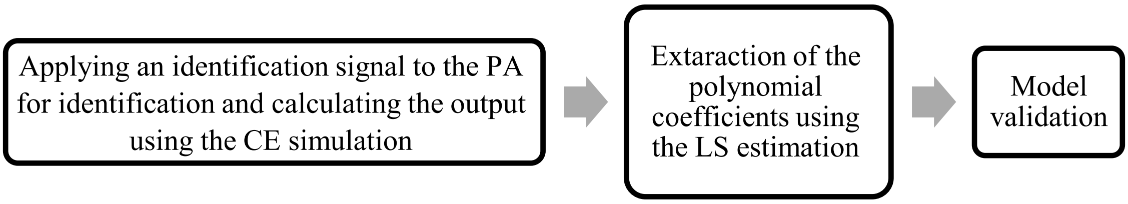


Fig. 2 PA modeling process.

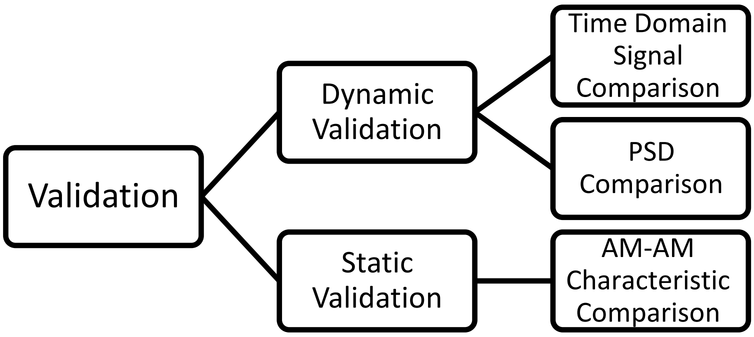


Fig. 3 Summary of the model validation process.

efficiency while the spectral regrowth of the output PSD is constrained to a threshold determined by the standard.

3.PA Modeling

The modeling and in fact, identification of the PA is a crucial part in the proposed technique. Although is nonlinear in terms of the input signal, fortunately, it is linear in terms of coefficients $b_{p,q,g}$, and therefore, these coefficients can be calculated by the least square (LS) method [17]. Here, to identify the PA model, first, we apply the identification signal $x_{id}[n]$ to the PA, and compute the PA output signal $y_{id}[n]$ using the CE simulation in the advanced design system (ADS) software [13]. Afterward, by the use of $x_{id}[n]$ and $y_{id}[n]$ samples, and employing the LS method, the coefficients of the GMP model are identified [17].

In order to have a reliable model, the derived GMP model must be validated. In this paper, we validate the derived model statically and dynamically. For the static validation, we compare the AM-AM characteristics of the GMP model and the harmonic balance (HB) simulation of the PA using the ADS software. Also, in order to validate the derived PA model dynamically, the validation signal $x_{val}[n]$ (which is different from the identification signal) is applied to this model, and the corresponding output signal is calculated. On the other hand, using the CE simulation in the ADS software, the PA output samples for the same input $x_{val}[n]$ are obtained. Then, the output signal of the GMP model is compared with the output signal of the CE simulation in the time domain and frequency domain (PSD) to validate the obtained model. The modeling process is illustrated briefly in Fig. 2. Also, Fig. 3 shows the model validation, which is the last part of the modeling process in Fig. 2.

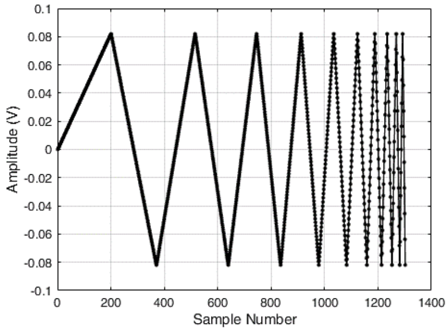


Fig. 4 Training Signal.

3-1- Sample PA Identification

As a sample PA, we use a 25W, 2.4 GHz, Doherty PA, designed in [10]. For the PA identification, we tried different signals, including 3G multitone, random signals, chirp signal, and triangular signal. Also, we tried different values for model parameters P, Q and G. The results of the validation tests showed that the triangular signal with increasing frequency over time, shown in Fig. 4, with $P = 11$, $Q = 2$ and $G = 1$ has the best results.

3-2- Sample PA Model Validation

As stated before, the derived model has to be validated from static and dynamic aspects. In static validation, the AM/AM characteristic of the model is compared with AM/AM characteristic obtained from Harmonic Balance (HB) simulation. Fig. 5 illustrates the normalized gain of the derived model (GMP) and the HB simulation in terms of output power. Moreover, to verify the dynamic behavior of the model (validation of memory effects), we used a 15

MHz, three-tone signal in the M-LINC system. In Fig. 6, the output signal of one of the outphasing branches is compared in the time domain by the use of the derived model and the CE simulation. Finally, the PSDs of the output signals of the outphasing system for both the derived model and the CE simulation are compared in Fig. 7. The results of comparisons in all three Figures verify the validation of the derived model.

4.Efficiency Maximization with Linearity Constraints

In the previous section, we derived the GMP model for the PA and obtained the output PSD of the PA. Our aim is to design a multilevel outphasing system by the modeled PA to maximize efficiency while the linearity constraints required by the standard are satisfied. One of the effects of the nonlinear PAs on the system is the spectral regrowth at the output of the power amplifiers [11]. Most of the wireless communication standards impose constraints on the spectral regrowth of the system using the ACLR which is a function of the output PSD of the system and determines the ratio of the amount of the distortion signal leaked into the adjacent channels to the amount of the signal in the main channel. Here we use a three-tone signal with 15 MHz of bandwidth and define the left and right ACLRs as

$$\begin{aligned}&ACLR_L(L)=\\&10\log_{10}\left(\frac{\max(P_{yy}(L,-15\text{MHz}<f<-10\text{MHz}))}{\max(P_{yy}(L,-7.5\text{MHz}<f<7.5\text{MHz}))}\right)\\&ACLR_H(L)=\\&10\log_{10}\left(\frac{\max(P_{yy}(L,10\text{MHz}<f<15\text{MHz}))}{\max(P_{yy}(L,-7.5\text{MHz}<f<7.5\text{MHz}))}\right)\end{aligned} \tag{6}$$

where $p_{yy}(L,f)$ is the PSD of the output signal of the outphasing system in the frequency range f using the levels vector L where the entries of L are given by

$$l_n=20\log_{10}\left(\frac{a_n}{a_{n-1}}\right),n=1,\dots,N. \tag{7}$$

We estimate $p_{yy}(L,f)$ by standard Welch method using an adequate length of the output signal of the system [18]. So, the optimization problem can be formulated as follows.

$$\begin{aligned}\max\quad & \text{efficiency(L)}\\ \text{subject to}\quad & \text{ACLR}_L\text{(L)<ACLR}_{Std}\\ & \text{ACLR}_H\text{(L)<ACLR}_{Std}\\ & L\le 0\end{aligned} \tag{8}$$

where $ACLR_{Std}$ is assumed as the required ACLR by the standard. In order to solve the optimization problem, since the defined problem is not convex. The PSO is an evolutionary algorithm for solving the non-convex problems, and more computationally efficient than the Genetic algorithm. In many applications, like resource allocation problems in wireless communications, PSO is employed with suitable performance. In this algorithm, a swarm of particles moves iteratively through the feasible set of the optimization problem to find the optimum point [19], [20]. We use PSO with the optimization parameters listed in Table 1 [21]. Also, to transform the constrained problem into an unconstrained one, we use the penalty method to add the constraint functions

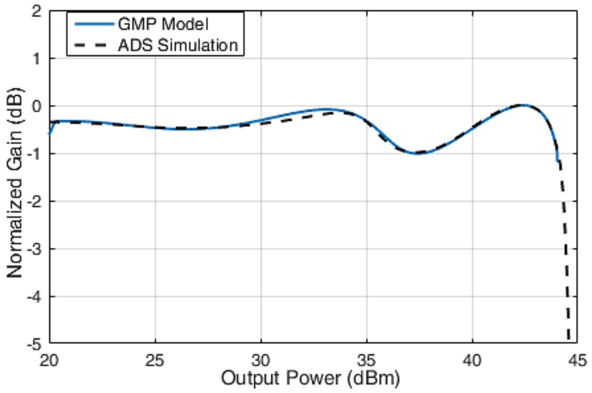


Fig. 5 Gain comparison between GMP model and ADS simulation.

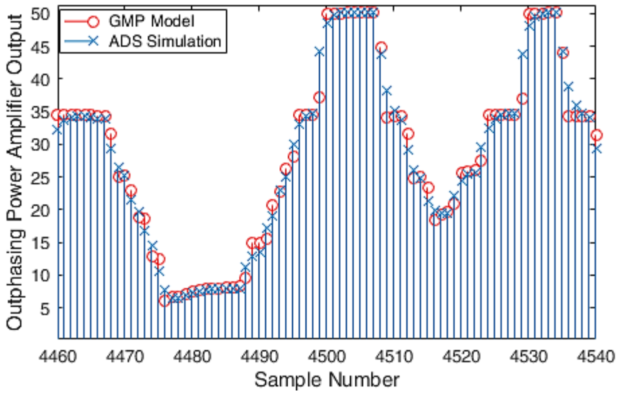


Fig. 6 Comparision of the outputs of the outphasing PAs using the GMP model and ADS simulation.

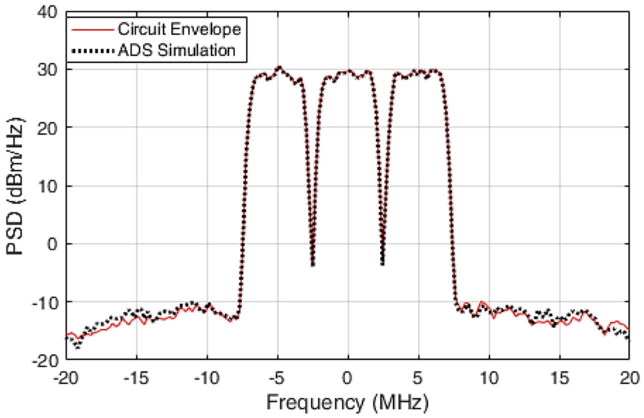
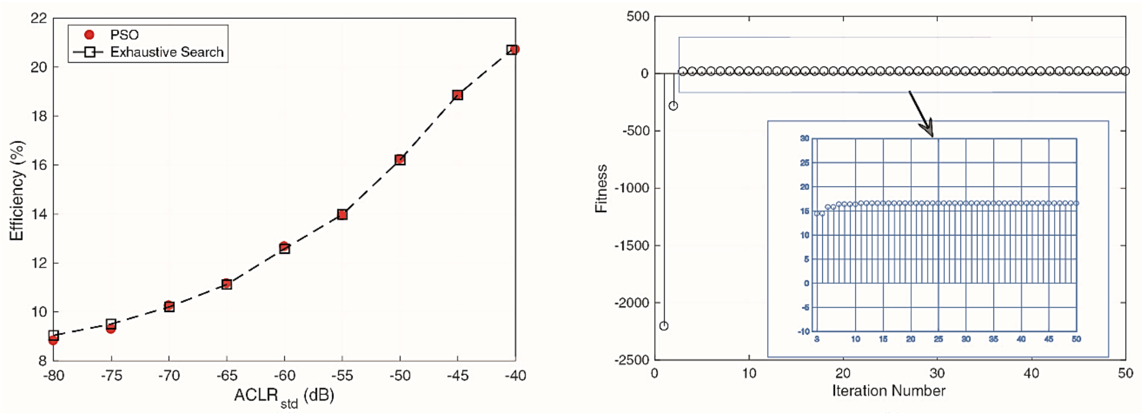


Fig. 7 Outphasing system PSD comparison using ADS simulation and GMP model.



(a) (b)

Fig. 8 (a) Comparison of the PSO method with exhaustive search, (b) the fitness values in different iterations for the constraint $ACLR_{Std}$= -50 dB.

to the objective function by a penalty term, which yields

$$\text{fitness=efficiency-10}\begin{pmatrix}\max(ACLR_L\text{-ACLR}_{Std}, \\ ACLR_H\text{-}ACLR_{Std}, 0)\end{pmatrix}^3 . \qquad (9)$$

Fig. 8 (a) compares the results of a three-level outphasing system using the PSO method with the results of the exhaustive search over 10000 uniformly distributed set of outphasing levels of that system. As it can be seen, the results of the PSO method are near the results of the exhaustive search, whereas the result of PSO is achieved with fewer function evaluations (500 against 10000). Fig. 8 (b) shows the fitness value versus the iteration number for the outphasing system with six levels and $ACLR_{Std} = -50\,\text{dB}$. It can be seen that the optimization problem has converged in about ten iterations. The optimum levels, l_1 to l_5 for this optimization are 0, -2.9, -0.34, -1.38 and 0 dB, respectively. Considering , the three nonzero elements of the optimum point means that the optimized M-LINC system for -50 dB of ACLR has four levels.

For investigation of the effect of ACLR limit on the obtained efficiency, the optimization problem is solved for different values of ACLR limits and the results are plotted in Fig. 9. As can be seen, when the ACLR constraint becomes more relaxed, the optimized number of levels and the obtained efficiency increases.

The linearity of the proposed method is compared with the previous works on the M-LINC systems in Table 2. Although previous works cannot control the linearity-efficiency trade-off in M-LINC systems, the proposed method can maintain the linearity while finding the maximum possible efficiency. As it can be seen in the Table, the ACLR of the proposed method is adjustable in the range [-60,-35] dB, and can be as excellent as -60 dB, which is better than other works in the Table.

5. Conclusion

In this paper, we focused on the efficiency maximization of M-LINC systems with linearity constraints. Considering that most of the wireless communication standards impose linearity constraints on the transmitters using the ACLR limits, (which is a function of the output PSD of the system) we proposed the use of GMP models for the PAs to calculate the PSD of the output signal. Also, we provided a robust PA modeling process which validates the dynamic and static behaviors of the obtained model. As an example, we optimized an M-LINC system with 25 W Doherty PAs for a three-tone 15 MHz signal with different ACLR limits. The optimization was performed using the PSO method. The results showed that the algorithm converges in a few iterations. Results showed

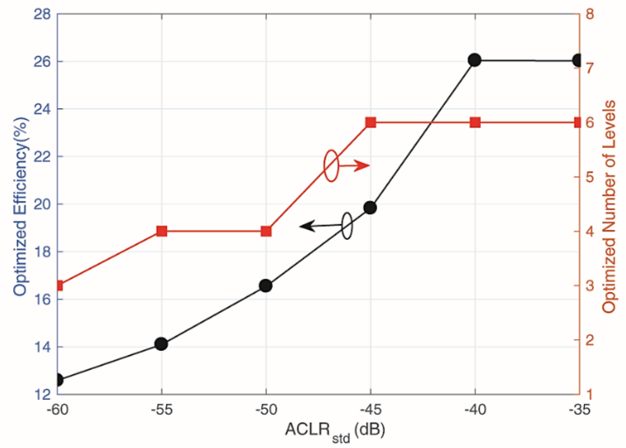


Fig. 9 Optimum efficiency of the proposed outphasing system for the 3G Multitone signal in terms of ACLR limit.

Table 1. PSO optimization parameters (for more details, please refer to [21]).

Parameter	Value
Inertia Coefficient	0.99
Cognitive Coefficient	1.99
Social Coefficient	1.99
Number of Particles	10
Number of Iterations	50

Table 2. Comparison of this work with recent published M-LINC papers.

Paper	Signal	Bandwidth	ACLR
[7]	WLAN	20 MHz	-40 dB
[22]	LTE	5 MHz	-50 dB
[23]	LTE	20 MHz	-42.4 dB
[24]	LTE	10 MHz	-31.5 dB
This Work	3G Multi-Tone	15 MHz	-60 dB<ACLR<-35 dB

that relaxing the ACLR constraint results in more efficiency and vice versa, which unveils the existing trade-off between linearity and efficiency in M-LINC systems.

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