Comparison of Models for Multiple Nonlinear Power Amplifiers in Active Antenna Arrays

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Abstract— **The methods used to model nonlinear power amplifiers are many and varied. With the introduction of active antenna arrays as a solution to increasing the capacity of cellular networks new strategies need to be developed to model their multiple signal paths. Models for power amplifiers in active antenna arrays will be required to have similar performance in terms of speed and accuracy as before. To achieve this, will require a reduction in the number of coefficients in each signal path relative to the number of PAs in the active antenna array, or alternative modeling strategies. In this paper we will present some of the reasons for requiring the ability to predict each PA output in an active antenna array, a shortlist of models which can be used to model the outputs of all PAs simultaneously and efficiently. Finally the relative performance of these models are compared in terms of their size, accuracy and speed.**

Keywords— Power amplifiers, , predistortion, active antenna arrays.

I. INTRODUCTION

Active antenna arrays (AAA) have the potential to significantly increase the capacity of wireless communication networks through their use of beamforming. While beamforming can be used to take advantage of the spatial domain to increase capacity, effort is required to maintain an accurate beampattern. Fundamentally the accuracy is dependent on the amplitude and phase relationships between the elements of the array [1]. Calibration algorithms for correcting linear gain mismatch or phase offset have been considered previously, however these are not sufficient to correct for nonlinearity caused by different power amplifiers.

In some power amplifier architectures it is required to drive them at power levels where nonlinearity occurs in order to achieve as efficient operation as possible. Non-ideal behaviour of a power amplifier due to thermal effects, bias circuits or charge trapping can cause distortion in the amplified output signal also. Pre-distortion techniques can be employed to distort the input signal in such a way that the PA will provide a linear output signal. These algorithms vary in their capabilities and importantly in size, however all are ultimately aimed at providing sufficient accuracy to meet spectral mask performance using as few weights as possible. A first step in identifying the limitations and size of a pre-distortion algorithm can be to use its structure inverted, as a model for the PA.

Although PA models in recent years have been demonstrated to have adequate performance for individual PAs using fewer and fewer parameters, the models for multiple PAs have not been studied in as great a detail. In active antenna array systems there can be as many as 64 radiating elements. If each element of the 64 antenna element array is supplied by a separate PA, it could be assumed that the system can be modeled by increasing the total number of coefficients by a factor of 64 also. However, it does not automatically hold that this is the most efficient way to model all PAs simultaneously.

Space mapping as proposed by Bandler et al. [2] has shown promise in its application to modeling and design optimization for such systems where there may be some common characteristics in multiple parts of a system. Space mapping intelligently links companion models termed: "coarse" and "fine" models with the ultimate aim of the optimization stage being the extraction of a satisfactory model with a minimum number of computationally "fine" model evaluations. Application of space mapping requires the construction of both the fine and coarse models, determination of what these models are and the mapping or relationship between these models is not always obvious. Therefore a number of model arrangements should be investigated initially.

In this paper we investigate 3common PA models, namely the AM/AM & AM/PM, modified Volterra series (MVS) and time delay neural network (TDNN). The capabilities of the models for characterizing multiple PAs in an active antenna array will be compared in terms of accuracy, speed and the total number of coefficients required in each case.

II. ANTENNA ARRAY MODELING STRATEGY

Power amplification in an antenna array with multiple radiating elements can be carried out in a number of different ways. The main difference between the different options being the number of separate PAs that are used. An obvious option is to use one PA for each radiating element such that each transmission path is physically separate from the others as shown in Figure 1(c). Other options such as Figure 1(b) can see multiple PAs supplying multiple radiating elements or in Figure 1(a) a single PA is used to supply all radiating elements.

In cases where a PA is used to feed multiple radiating elements, a great deal of care needs to be taken in the design and fabrication of the tracks used to carry the signals out from the PA in order to maintain signal synchronization across all paths. Indeed the benefits of having a PA on each path include a reduction in the fabrication cost of subsequent feeder lines or cables from the PA and a certain degree of redundancy in the system as a whole, since a PA failure will only disable one path. A functional antenna array, similar to the latter option can be achieved through the generation of multiple input signals and also the use of six port coupler structures to enable the accurate synchronization of the PA output signals [3].

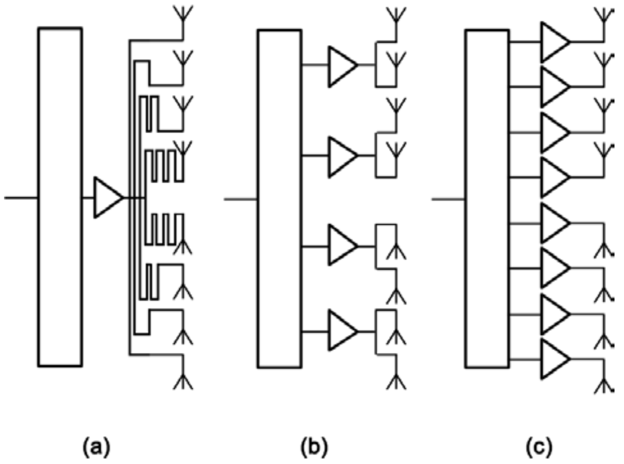

Fig. 1. Examples of power amplifier arrangements in active antenna arrays

Adopting an antenna array structure which has PAs in each signal path, there is a possibility that the output from each signal path will not be identical. If the difference in signals supplied to the radiating elements across the antenna array have greater than 5º phase or 0.5 dB gain mismatch then the radiated beam pattern is not generated as expected. Mismatch between radiating elements has been reported to reduce the capacity by ~12% or ~28% for ±3º and ±6º respectively [4]. Although it has been demonstrated previously that it is possible to synchronize these signal paths and correct the linearly related amplitude mismatch, this is not sufficient to correct the differences between signal paths caused by the nonlinear responses of the PAs. It is therefore important that an accurate model for the system, which can reproduce the nonlinear distortion and memory effects generated in the PAs can be constructed to investigate the extent of the beam-forming problem.

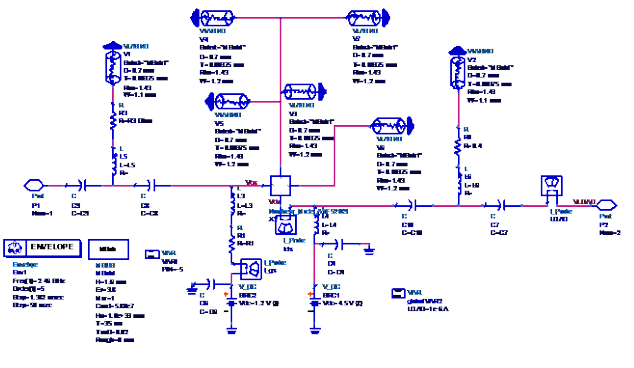

Fig. 2. Schematic for Class AB PA circuit used to generate the input and output signal datasets for multiple PAs

To this end we investigate an 8-by-2 antenna array containing 16 power amplifiers in this work. Each power amplifier is fed the same input signal, and it is their respective outputs that will be used to extract the equivalent behavioural model for the array of power amplifiers. Initially it is assumed that the power amplifier outputs are measured simultaneously. In this way individual models can be extracted for each power amplifier or an aggregated model can be extracted to reproduce all PA outputs. Differences which arise in practice such as the variation in passive component values and active devices within the quoted manufacturers tolerance ranges are introduced into the simulations.

In order to replicate a likely variation between the signal paths 16 random variations of component values between manufacturer tolerance ranges are generated. The 16 amplifiers used in this example are class AB power amplifiers using the ATF52189 from Avago Technologies. These power amplifiers are designed to amplify a signal at 2.46 GHz. This EpHEMT is chosen as it offers high linearity, low cost and is high reliability with a predicted mean time to failure of 300 years for a channel temperature <100deg and with a 90% confidence level. The high reliability and linearity of the transistor are of primary concern when the device is to be used in a tower mounted basestation. Input and output 50 ohm impedance LC-matching networks are required to deliver the maximum power to the load. The circuit diagram for the PA used in simulations is shown in Fig. 2. The nonlinear ADS model for the ATF52189 was based on the advanced Curtice FET model and covers both linear and nonlinear modes of operation [5]. To meet the goals for high gain and high linearity, a relatively high drain current is selected. It was found from simulation of this PA that using component values with a tolerance range of +/- 5% is sufficient to cause enough amplitude imbalance between signal paths to cause distortion in the beamformed radiation pattern from the antenna array [6].

III. Power Amplifier Model Options

Three models are used in this work namely: AM/AM & AM/PM, modified Volterra series [7, 8] and time delay neural network (TDNN) models [9]. For clarity the equations for each of the models used are listed in (1-3).

AM/AM & AM/PM Model:

$$y(n) = |y(n)|\, e^{(\phi_{x(n)} + \triangle\phi_{y(n)})}$$

$$|y(n)| = \sum_{j=0}^{P} a_j\, |x_j(n)|^j \qquad (1)$$

$$\triangle\phi_{y(n)} = \sum_{j=0}^{P} b_j\, |x_j(n)|^j$$

where y is the output, x is the input signal, Φ is the phase and | | denotes the absolute value. a and b are the coefficients of the polynomials used to represent the AM/AM and AM/PM curves respectively. P is the order of nonlinearity.

Modified Volterra Series Model:

$$\begin{aligned} y(n) \;=\; & \sum_{p=1}^{P} h_{p,0}(0,\ldots,0)x^p(n) + \sum_{p=1}^{P}\left\{\sum_{r=1}^{p}\left[x^{p-r}(n)\right.\right. \\ & \left.\left.\sum_{i_1=0}^{M}\cdots\sum_{i_r=i_{r-1}}^{M} h_{p,r}(0,\ldots,0,i_1,\ldots,i_r)\prod_{j=1}^{r} x(n-i_j)\right]\right\} \end{aligned} \qquad (2)$$

where y is the output, x is the input, h denotes the Volterra kernels. P is the order of nonlinearity and M is the memory depth of the model.

Time Delay Neural Network Model:

$$y(n) = I_{out}(n) + jQ_{out}(n)$$

$$I_{out_k}(n) = f\left[\sum_{j=1}^{m} w_{kj}^2 \; g\left[r_j(n)\right] + b_k^2\right]$$

$$Q_{out_k}(n) = f\left[\sum_{j=1}^{m} w_{kj}^2 \; g\left[r_j(n)\right] + b_k^2\right] \tag{3}$$

$$r_j(n) = \left[\sum_{i=0}^{M-1} v_{ji}^1 I_{in}(n-i) + b_i^1 + \sum_{l=0}^{M-1} u_{jl}^1 Q_{in}(n-l) + b_l^1\right]$$

where y is the output, the input signal I_{in} and Q_{in} correspond to the real and imaginary components of the input signal, b denotes the bias weight u,v,w denote the neuron weights.

Both the AM/AM & AM/PM model and the modified Volterra series can be extracted for each PA individually. These models have as a result a single complex input signal and corresponding complex output signal. In the case of the TDNN it was decided that the most appropriate strategy would be to extract coefficients for one network with a single complex input and 16 complex output signals.

Once the order of nonlinearity and memory depth are estimated for a given signal power level, the coefficients for each model are determined. In order to provide consistency in the comparison of the models, the complex envelope of the baseband signal in the time domain is used to extract all models and validate them. As a result the AM/AM & AM/PM model is extracted using polynomial curve fitting of the AM/AM and AM/PM curves when the instantaneous samples are plotted against one another. The modified Volterra series in this instance is extracted using adaptive filter RLS training algorithm. Finally the neural network model coefficients were extracted using the Levenberg-Marquardt training algorithm.

IV. Results

Normalised mean square error (NMSE) is a common figure of merit used to quantify the performance of a model. In the case of a system simulator there is also a need to quantify the number of coefficients used in the model and to a certain extent the length of time it will take to extract the model and subsequently use the model in simulation. Comparing these figures will give a general overview of the models presented in this work.

Selecting an operating power level at which the PA is operating in a mildly nonlinear mode, each of the 3 models are dimensioned to characterise the PA. It was observed that although additional coefficients are used in the modified Volterra series, its accuracy compared with the AM/AM & AM/PM model was not improved. In both the AM/AM & AM/PM model and the modified Volterra series model the extraction is performed on the input and output dataset pairs for each PA individually.

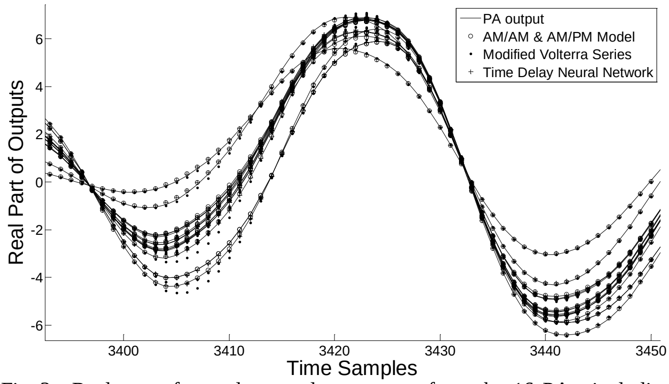

Fig. 3. Real part of complex envelope outputs from the 16 PAs, including estimates from AM/AM & AM/PM models, modified Volterra series models and time delay neural networks.

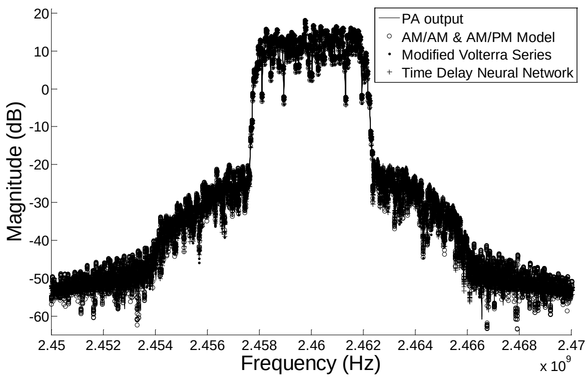

Fig. 4. Frequency spectra of complex envelope outputs from the 16 PAs, including estimates from AM/AM & AM/PM models, modified Volterra series models and time delay neural network.

TABLE I. Comparison of Models for Active Antenna Arrays

Model	No. of Weights	Average NMSE (dB)	Simulation Time (s)
AM/AM & AM/PM	192	-32.7549	2.928
Modified Volterra	224	-30.513	88.192
TD Neural Network	207	-32.5886	0.242

The AM/AM & AM/PM models have 6 real value coefficients for each of the 16 power amplifiers. The modified Volterra series is set to have 14 complex coefficients for each power amplifier. Finally the TDNN is set to have 1 hidden layer with 5 neruons and 32 output neurons to supply the 16 real and 16 imaginary components of the output signals separately.

V. Conclusions

In this paper we have presented a test case for active antenna arrays with 16 power amplifiers. Three model strategies are presented for use with this test case mindful of the desire to minimize the total number of coefficients and thus reduce the amount of time needed to extract the models and subsequently use them in simulation. It is shown that in this situation where the PAs are mildly nonlinear the most efficient model to use is the AM/AM & AM/PM model. Although simulation time is a useful comparison to make, it is the number of coefficients required by each model and the relative accuracy that the models can achieve that are most important. The length of time taken to perform a simulation using a modified Volterra series for all PAs is shown to be much greater than the time required to simulate using the time delay neural network. It is expected that the difference would not be so large if parallelization of the computations were made in the case of the modified Volterra series.

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