Abstract—With the increase in demands of the multi-band and ultra-wideband based transmitter, the research interest in power amplifiers (PAs) is moving towards the designing of multi-band and ultra-wideband PAs. This leads to unprecedented challenges such as the possibility of multiband transmission at harmonic frequencies. This brief investigates and presents the novel DPD models for linearization of a previously uninvestigated case of concurrent tri-band PA at harmonic frequencies. This brief analyzes the intermodulation (IMD) terms which are producing harmonic distortions and proposes three-dimensional harmonic memory polynomial (3D-HMP) and harmonic Volterra spline (3D-HVS) models for mitigation of in-band harmonic, cross-modulation, and intermodulation distortions. The results show that the proposed 3D-HMP and 3D-HVS DPD models have linearization performance in terms of adjacent channel power ratio (ACPR) below -50 dBc.

Index Terms—Behavioral Modeling, concurrent tri-band transmitter, digital predistortion, harmonic distortion, intermodulation distortion, ultra-wideband power amplifiers (PAs).

I. INTRODUCTION

The evolution of the Wireless Communication system requires multi-band transmission with better modulation schemes [1]. The modulation schemes such as orthogonal frequency division have high peak-to-average power ratio (PAPR). This high amplitude variation leads to the generation of nonlinearity mainly due to power amplifiers (PAs). Also, the multi-band transmission requires that the PA of the transmitter operates and supports concurrent multi-band frequency ranges [2]. Different scenarios of frequencies allocations by 3GPP standard will be used to better illustrate the problem and the need to mitigate the problem of inter-band distortion as well as its impact on the quality of the downlink (DL) signal and/or uplink (UL) signal at the input of or output of the RF front-end. For example, in inter-band carrier aggregation (CA), the harmonics generated from E-UTRA Band 8 DL (925–960 MHz) may intervene with band 3 DL (1805–1880 MHz) over the European region. Similarly, the harmonics generated from E-UTRA Band 29 DL (717–728 MHz) may intervene with band 4 DL (2110–2155 MHz) over the North American region.

II. PROPOSED DPD MODELS

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Similarly, the harmonics generated from E-UTRA Band 28 UL (703–748 MHz) may intervene with band 11 UL (1427.9–1447.9 MHz) and band 11 UL (1427.9–1447.9 MHz) over the Asian region [3]. In the forthcoming 5G communication system, the frequency bands operation would extend from 3.5 GHz to 6 GHz in sub-6 GHz radio frequency or possibly 30–100 GHz millimeter-wave frequency band. There might be the possibility of further increase in harmonic interference. The combination of high PAPR [4] and operation over ultra-wideband frequency range adds to the distortions like in-band harmonic distortions, cross-modulation distortions (CMDs), and intermodulation distortions (IMDs) of PA.

Digital Predistortion (DPD) is the well-established technique for linearization of multi-band PA [4]–[17]. In [7], the two-dimensional DPD (2-D) model was proposed for linearization of concurrent dual-band transmitter. In this method, a frequency selective approach is used to linearize both bands individually. Most of the multi-band DPD models use this approach. In addition to nonlinear distortion, hardware impairments such as the dc offset, in-phase and quadrature-phase (I-Q) imbalance were mitigated using a novel 2-D Enhanced Cartesian memory polynomial model (2DECMPM) [8]. In [9], two-dimensional harmonic memory polynomial (2D-HMP) was proposed for linearization of concurrent dual-band transmitter at harmonic frequencies. In [10], 2-D curtailed harmonic memory polynomial (2D-CHMP) was proposed. This model had almost comparable linearization performance to the 2D-HMP model with reduced model’s complexity. In [11], a novel DPD model was proposed for nonlinear compensation of harmonics, and IMD terms in concurrent dual-band transmitter. In [12], three-dimensional memory polynomial (3D-MP) was proposed to linearize concurrent tri-band transmitter. This model was modified to 3D Phase aligned Pruned Volterra Model (3D-PAV) in [13] for better linearization of PA. There are few more DPD models proposed to linearize concurrent tri-band transmitter [14]–[16]. However, in these papers [12]–[16], carrier signals are not transmitted at the harmonic frequencies in the concurrent tri-band transmitter as shown in Fig. 1(a). In that scenario, out-of-band IMDs and harmonic terms can be filtered out. If carrier signals are transmitted at harmonic frequencies as shown in Fig. 1(b), in addition to in-band CMDs and IMDs, in-band harmonic distortions would also be present at the output of tri-band PA.

This paper presents a novel three-dimensional harmonic memory polynomial (3D-HMP) and Volterra spline (3D-HVS) DPD models for behavioral modeling and linearization of a concurrent tri-band transmitter operating at harmonic frequencies. The proposed models include the IMD terms which are generating the harmonic distortions in the concurrent tri-band transmitter. These proposed models aim to linearize PA in presence of in-band IMDs, CMDs, and harmonic distortions.

This paper is organized as follows: Section II discusses the state-of-the-art 3D DPD models, analyzes the harmonic distortions produced and defines 3D-HMP and 3D-HVS DPD models. Section III describes the measurement testbed used for tri-band PA.
are the coefficients, are transmitted at carrier frequencies are the baseband modulated input signals, (1) \[ y_1(n) = \sum_{k=0}^{M-1} \sum_{j=0}^{1} \sum_{i=0}^{K} \sum_{r=0}^{1} C_{k,j,i}^{(l)}(n-r)x_1(n-r)^{(-1)}x_1(n-r)^{(-1)}x_1(n-r)^{(-1)} \] where \( M \) is the memory depth, \( C_{k,j,i}^{(l)}(n-r) \), are the coefficients, \( x_1(n) \) and \( x_1(n) \) are the baseband modulated input signals, \( y_1(n) \) is the baseband modulated output of the LB using 3D-PA model, and \( K \) is the nonlinearity order. The outputs of middle-band (MB) and upper-band (UB) can be easily obtained using a similar expression as in (1).

In the 3D-PAV [13], the baseband bi-dimensional model was constructed considering only the input carrier signals and the IMD components that fall within the three fundamental frequency bands. The output of a lower-band (LB) is

\[ y_1(n) = \sum_{k=0}^{M-1} \sum_{j=0}^{1} \sum_{i=0}^{K} \sum_{r=0}^{1} C_{k,j,i}^{(l)}(n-r)x_1(n-r)^{(-1)}x_1(n-r)^{(-1)}x_1(n-r)^{(-1)} \]

where \( M_1 \) and \( M_2 \) are the memory depths, and \( C_{k,j,i}^{(l)}(n-r) \) are the coefficients of the 3D-PAV model.

B. Analysis of Harmonic Distortions

Fig. 3(a) shows the output of a PA where three modulated complex input signals \( x_1, x_2, x_3 \) are transmitted at carrier frequencies \( f_1 = 1.2 \text{ GHz}, f_2 = 2.4 \text{ GHz}, \text{ and } f_3 = 3.6 \text{ GHz} \). The
TABLE I

| IMD Terms in Concurrent Tri-band Transmitter |
|------------------|------------------|
| Freq. (GHz) | IMD Terms |
| 0.9 | \( x_i(n)x_j^*(n)e^{j2\pi f_d n}\) |
| 1 | \( x_i(n)x_j^{*(n)}e^{j(2\pi f_d n)}\) |
| 1.1 | \( x_i(n)x_j^*(n)e^{j(2\pi f_d n)}\) |
| 1.3 | \( x_i(n)x_j^{*(n)}e^{j(2\pi f_d n)}\) |
| 2.3 | \( x_i(n)x_j^{*(n)}e^{j(2\pi f_d n)}\) |
| 2.6 | \( x_i(n)x_j^{*(n)}e^{j(2\pi f_d n)}\) |

Distortions fall at the harmonic frequencies. In order to analyze these distortions, we have shifted first and third carrier signals to be able to observe and quantify the harmonic distortions. This frequency shift is kept small as compared to carrier frequency i.e \( \Delta < f \) for better observation. Now, three modulated complex input signals \( x_1, x_2, x_3 \) are transmitted at carrier frequencies \( f_1 = f + \Delta = 1.2 + 0.2 = 1.4 \) GHz, \( f_2 = 2f = 2.4 \) GHz, and \( f_3 = 3f + \Delta = 3.6 + 0.1 = 3.7 \) GHz respectively. Fig. 3(b) shows the IMDS generated around these carrier signals. The IMDS are at 0.9, 1.1, 1.3, 2.3, 2.6, 2.7, 2.8, 3.4, 3.5, 3.8, and 4.2 GHz. Table 1 shows the IMDS corresponding to these frequencies.

In practical scenarios of harmonic CA modulated signals, some of the IMDS and CMDs generated by the PA would fall within or nearby the bands of the carriers of the input signals. To illustrate the above, the IMD terms \( \omega_1 - 2\omega_1, \omega_2 - \omega_1, 2\omega_1 - \omega_2, \) and \( \omega_3 - \omega_1 \) fall close by \( \omega_1 \). Similarly, these IMD terms \( \omega_2 - \omega_1, 2\omega_1 - \omega_2, \omega_1 + \omega_2 - \omega_2, \) and \( \omega_2 + \omega_3 \) fall close by \( \omega_2 \). When the shift from first and third harmonic is 0, i.e. \( \omega_1 = \omega_2 = 2\omega_1 \), \( \omega_2 = 3\omega_1 \), then these IMD terms fall directly on \( \omega_1 \), \( 2\omega_1 \) and \( 3\omega_1 \) frequencies.

C. Proposed DPD Models for Harmonic Distortions

The 3D-PM and 3D-PAV models do not contain these IMD terms and thus would be insufficient to capture harmonic distortions when the third modulated complex input signals are transmitted at harmonic frequencies \( \omega_1 = \omega_2 = 2\omega_1 \), and \( \omega_3 = 3\omega_1 \).

By including the above IMD terms in the model, the output of the transmitter would be

\[
y_i(n) = \sum_{k=0}^{M-1} x_i(n-k)H_i^0(n-k) + \sum_{r=1}^{M-1} x_i(n-r)x_{j}^{*(n-r)}H_i^{(r)}(n-r) + \sum_{r=1}^{M-1} x_i(n-r)x_{j}^{*(n-r)}H_i^{(r)}(n-r) + \sum_{r=1}^{M-1} x_i(n-r)x_{j}^{*(n-r)}H_i^{(r)}(n-r)
\]

where \( K_i, K_j, K_k \) are the coefficients for the \( p \)th IMD term of \( r \)th band of the 3D-HMP model.

To model the nonlinearity, instead of polynomial, cubic splines can also be used, which is notified as 3D-HVS model

\[
H_i^{(r)}(n-r) = \sum_{k=0}^{M-1} \sum_{j=p}^{M-1} \sum_{j=p}^{M-1} d_{r,j,k,p}^{(i)} \phi_{j,p} \left( \|x_i(n-r)\|, \|x_{j}^{(n-r)}\|, \|x_{j}^{(n-r)}\| \right)
\]

where

\[
\phi_{j,p} \left( \|x_i(n-r)\|, \|x_{j}^{(n-r)}\|, \|x_{j}^{(n-r)}\| \right) = \sum_{k=0}^{M-1} \sum_{j=p}^{M-1} \|x_i(n-r)\| - \|x_{j}^{(n-r)}\|
\]

where \( \|x_i(n)\| \) is the value of the \( x_i(n) \) at the knot \( k, x_{j}^{(n)} \) is the value of \( x_j(n) \) at the knot \( j \) and \( x_j^{(n)} \) is the value of \( x_j(n) \) at the knot \( i \). \( K_j \) denotes the number of splines [17].
TABLE II
BEHAVIORAL MODELING RESULTS FOR DIFFERENT MODELS

<table>
<thead>
<tr>
<th>Model</th>
<th>LB</th>
<th>MB</th>
<th>UB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NMSE (dB)</td>
<td>ACEPR (dBc)</td>
<td>NMSE (dB)</td>
</tr>
<tr>
<td>Proposed</td>
<td>-41.62</td>
<td>-54.75/ -54.47</td>
<td>-42.83</td>
</tr>
<tr>
<td>Proposed</td>
<td>-41.69</td>
<td>-55.62/ -55.36</td>
<td>-42.92</td>
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TABLE III
COEFFICIENTS COMPARISON BETWEEN MODELS

<table>
<thead>
<tr>
<th>Model</th>
<th>General case</th>
<th>Test Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D-MP</td>
<td>MK (K + 1)(K + 2)/2</td>
<td>672</td>
</tr>
<tr>
<td>3D-PAV</td>
<td>K(K + 1)(K + 2)/2 + 3M,M_s(K - 2)(K - 1)K/2</td>
<td>2328</td>
</tr>
<tr>
<td>3D-HVS</td>
<td>15M(K_s + 1)^2</td>
<td>3840</td>
</tr>
<tr>
<td>3D-HMP</td>
<td>5MK(K + 1)(K + 2)/2</td>
<td>3360</td>
</tr>
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</table>

TABLE IV
DPD RESULTS FOR DIFFERENT MODELS

<table>
<thead>
<tr>
<th>Model</th>
<th>LB</th>
<th>MB</th>
<th>UB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NMSE (dB)</td>
<td>ACPR (dBc)</td>
<td>NMSE (dB)</td>
</tr>
<tr>
<td>3D-MP DPD</td>
<td>-21.54</td>
<td>-40.41/ -34.67</td>
<td>-23.48</td>
</tr>
<tr>
<td>Proposed</td>
<td>-40.18</td>
<td>-52.41/ -52.22</td>
<td>-41.29</td>
</tr>
</tbody>
</table>

III. MEASUREMENT SETUP

Fig. 4 shows the measurement setup used for the concurrent tri-band transmitter. It consists of NI transmitter (PXIe-1075), RF power combiner, ZHL-42 RF PA, attenuators, and R&S FSW spectrum analyzer as a transmitter observation receiver. Three different LTE signals of bandwidth 30 MHz, 20 MHz, and 15 MHz with PAPR of 12.86 dB, 13.02 dB, and 12.98 dB respectively are used. NI transmitter (PXIe-1075) has three RF channel outputs (NI-5793). These three RF channels are phase synchronized by reference clock of the transmitter. 30 MHz 101 LTE signal is transmitted at 1.2 GHz, 20 MHz 1001 LTE signal is transmitted at 2.4 GHz, and 15 MHz 101 LTE signal is transmitted at 3.6 GHz. These three RF signals are combined by a RF power combiner and are used to drive ZHL-42 RF PA. ZHL-42 PA has 28 dBm output power at 1 dB gain compression and operating frequency range from 0.7 GHz to 4.2 GHz. The output RF signal of PA is attenuated and then captured by R&S FSW spectrum analyzer at 1.2 GHz, 2.4 GHz, and 3.6 GHz respectively. The reference clock from the transmitter is provided to the receiver for synchronization. R&S FSW spectrum analyzer down converts the RF signals to baseband. The output and input baseband signal of each frequency band are time aligned in Matlab software. The signal is further processed by Matlab software to perform DPD.

IV. RESULTS

A. Behavioral Modeling Results

Table II shows the behavioral modeling results for different models in terms of Normalized Mean Square Error (NMSE) and Adjacent Channel Error Power Ratio (ACEPR). ACEPR is a metric to measure out-of-band modeling performance in the frequency domain. It is defined as a ratio of error power in an adjacent channel (left or right or mean of both) to the signal power in the main channel [10]. NMSE is a metric for in-band modeling.
measured in the time domain [10]. For behavioral modeling, NMSE is measured between the measured output and modeled output signal.

From Table II, the 3D-HMP and 3D-HVS have better NMSE and ACPR performance as compared to state-of-the-art models, approximately 10–15 dB improvement in NMSE from 3D-PAV model, which is expected as the state-of-the-art models do not contain harmonic terms shown in section II-B. It is to be noted that 3D-MP model constitutes an only first term of (3), (4) and (5). These results are for $M=4$, $M_1=4$, $M_2=3$, $K=6$, and $K_S=3$. Table III shows the coefficients comparison between different models and it can be observed that inclusion of harmonic terms leads to higher number of coefficients with much better behavioral modeling performance.

### B. DPD Results

Table IV shows the linearization results for different models in terms of NMSE and Adjacent Channel Power Ratio (ACPR). ACPR is a ratio of power in the adjacent channel (left or right or mean of both) to the main channel power measured in the frequency domain [10]. For linearization, NMSE is measured between the received and transmitted signal [10].

From Table IV, the 3D-PAV DPD model has better NMSE and ACPR performance than 3D-PAV model. However, the 3D-PAV DPD’s NMSE performance is much lesser than the acceptable performance of -35 dB. The proposed 3D-HMP and 3D-HVS DPD models have better NMSE and ACPR performance as compared to 3D-MP and 3D-PAV DPD models. The NMSE and ACPR have improved approximately by 11–16 dB and 10–18 dBc from 3D-PAV DPD model. Fig. 5 shows the frequency power spectra of various DPD models’ outputs at the LB, MB, and UB. As it can be seen from the Fig. 5, the proposed 3D-HMP and 3D-HVS DPD models have much better ACPR performance.

### V. Conclusion

The 3D-HMP and 3D-HVS DPD models have been proposed and experimentally verified to mitigate the in-band harmonic distortions, CMDs, and IMDs generated by ultra-wideband PA when carrier signals are transmitted at harmonic frequencies in the concurrent tri-band transmitter. To establish the need of this DPD model, it is compared with the state-of-the-art DPD models. It has been experimentally verified that the state-of-the-art DPD models are not able to capture in-band harmonic distortions and their NMSE and ACPR’s performance are not meeting the acceptable performance. Whereas the NMSE and ACPR’s performance of proposed DPD models are improved approximately by 23–26 dB and 18–20 dBc respectively over without DPD signal. The complexity of the proposed DPD models can be reduced by pruning techniques like PCA.

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### References


