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Publication date	2016-05-27
Publication information	Yu, Chao, Honglei Sun, Xiao-Wei Zhu, and Anding Zhu. "A Channelized Sideband Distortion Model for Suppressing Unwanted Emission of Q-Band Millimeter Wave Transmitters." IEEE, May 27, 2016. https://doi.org/10.1109/MWSYM.2016.7540308 .
Conference details	2016 IEEE MTT-S International Microwave Symposium (IMS), San Francisco, California, USA, 22-27 May 2016
Publisher	IEEE
Item record/more information	http://hdl.handle.net/10197/8642
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Publisher's version (DOI)	10.1109/MWSYM.2016.7540308

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A Channelized Sideband Distortion Model for Suppressing Unwanted Emission of Q-band Millimeter Wave Transmitters

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Abstract — In this paper, a channelized sideband distortion model is proposed to suppress the unwanted emission of Q-band millimeter wave (mmWave) transmitters in wideband contiguous carrier aggregation scenarios. By employing this model, the compensating bandwidth or center frequency can be agilely controlled. Experiments were conducted on a 40 GHz mmWave power amplifier to validate this idea. The satisfactory performance proved that the proposed model is a promising candidate for future 5G applications.

Index Terms —5G, millimeter wave, power amplifier, Q-band, unwanted emission suppression.

I. INTRODUCTION

With the continuing development of wireless communication systems, data rate of the transmission will reach the level of 10 gigabits per second (Gbps) in the forthcoming fifth-generation (5G) communication systems. Such high transmission speed will inevitably require very wideband frequency spectrum. For instance, in the 802.11ac standard, the bandwidth configuration will reach 160 MHz or more in the near future. It is, however, impossible to obtain contiguous bandwidth in the current operating frequency bands to meet the needs no matter how much you would like to pay. Due to this reason, millimeter wave (mmWave) frequency bands, such as Q-band and E-band, gradually become promising candidates to achieve this goal, since there are wide frequency spectra available over these bands.

The same as that occurred in the existing cellular systems, the nonlinear distortion induced by the transmitter, mainly contributed by mmWave power amplifiers (PAs), not only introduces the in-band distortion, but also generates the spectrum regrowth that affects the received signal quality in adjacent channels. This issue becomes much severer in mmWave operation, since the modulated signal bandwidth is much wider at higher frequency bands, which leads the spectrum regrowth can spread to a very wide frequency range.

Various solutions, either at transmitter or receiver side, have been sought to resolve this issue. Because of simplicity and the low bandwidth resource required, compensating the unwanted emissions in receivers is considered as a good choice. As shown in Fig. 1, a replica of the distortion is directly generated in the baseband and subtracted from the received signal to recover the original receiver signal. Based on this concept, M. Omer et al. [1] proposed a filter-based

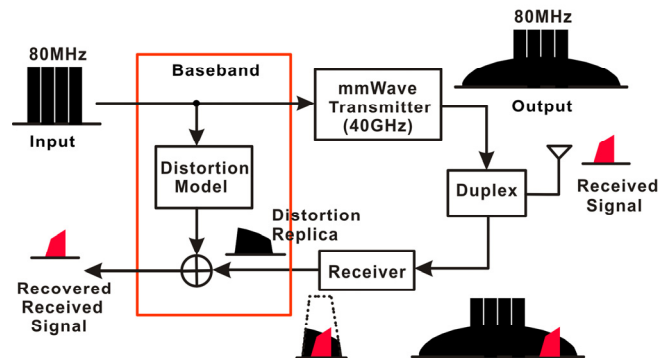


Fig. 1. Unwanted emission suppression in mmWave Transmitters.

Volterra model to deal with the sideband distortion centered around 2 GHz. A. Kiayani et al. [2] also proposed a similar technique to compensate the distortion. The idea of these approaches is mainly based on modeling and filtering. A nonlinear PA model is constructed first to generate the full nonlinear distortion, and then a bandpass filter is applied to filter out the other components to obtain the desired sideband distortion. Since the PA model often involves the high-order nonlinear terms, e.g., $|\tilde{x}(n)|^2\tilde{x}(n)$, $|\tilde{x}(n)|^4\tilde{x}(n)$, a high sampling rate is required. The bandpass filtering operation must also be conducted at a high sampling rate. Therefore, although these models are highly accurate, the occupied baseband signal processing bandwidth is very wide, e.g., normally multiple times the input signal bandwidth, which is difficult to achieve in broadband mmWave operation.

In this paper, we propose a novel channelized sideband distortion model to accommodate the contiguous carrier aggregation (CA) scenario with mmWave operation. By exploiting the CA characteristics of the signal, the input signal can be channelized into small pieces to accurately construct the corresponding basis functions of the unwanted emission. With the proposed approach, the signal processing bandwidth can be effectively reduced, resulting in low-complexity designs. The idea is validated on a 40 GHz Q-band mmWave PA.

II. PROPOSED METHOD

The wide bandwidth requirement problem of the existing solutions is caused by the nature of the distortion generation

mechanism. Because the full contiguous signal is used as input, the output of the PA model inevitably spreads over a very wide bandwidth due to the nonlinear process. If we re-look at the signal, we can find that this is not necessary the only way to construct the model. Because in carrier aggregation the input signal is actually composed from multiple inputs, for instance, 80 MHz is composed of four 20 MHz subcarrier signals. This means that the input signal can be easily decomposed into multiple sub-signals, or we can treat the signals separately before aggregation. If we take advantage of this characteristic of the signal, we can work out a new model to generate the sideband distortion induced by the transmitter PA, as described below.

Let's use the 80 MHz CA signal as an example again, shown in Fig. 2a. The signal includes four 20 MHz subcarriers. Considering the four subcarrier signals are independent, it is possible to separate them into smaller channels. In this case, we decompose the signal into two channels, each including two subcarriers. The gray regions represent the channels, simply denoted as ch1 and ch2, and the original input signal can then be represented by

$$\tilde{x}(n) = \sum_{k=1}^K \tilde{x}_k(n) e^{-j2\pi f_k n T} \quad (1)$$

where $\tilde{x}(n)$ is the baseband equivalent representation of input signal, and $\tilde{x}_k(n)$ is the baseband equivalent representation of the k^{th} channelized input signals. Besides the input signal, the distortion in the output can also be channelized, e.g., as ch3 and ch4, shown in Fig. 2a. The unwanted emission to be compensated is located at the received band that can fall in one of distortion channels, e.g. in this example, we assume it is located at channel 3. Now, if we treat the signal at each channel separately, the distortion in each channel can be treated as that generated from intermodulation products of the main signal channels, as shown in Fig. 2b. This leads that the multi-band and dual-basis modeling approached presented in [3], [4] can be employed.

Similar to the concept of the dual-basis functions used in [4], we now use the channelized inputs as independent baseband inputs to build the model bases to map input to output. Firstly, we build the first basis function to map the frequency components from the two inputs to the sideband distortion channel. In the example, as shown in Fig. 2, the unwanted emission is located at channel 3, which falls in the third order intermodulation zone. The third-order basis function can thus be used. Because the third-order intermodulation products occupy three times input bandwidth, all the basis functions, whose output occupies channel 3, must be included. In this case, there are three basis functions to be included: two in channel 2 and one in channel 3, as shown in Fig. 2c.

For channel 2, the basis functions are,

$$\begin{cases} B_{1,\text{ch2}}^{(1)}(n) = |\tilde{x}_1(n)|^2 \tilde{x}_2(n) \\ B_{1,\text{ch2}}^{(2)}(n) = |\tilde{x}_2(n)|^2 \tilde{x}_1(n) \end{cases} \quad (2)$$

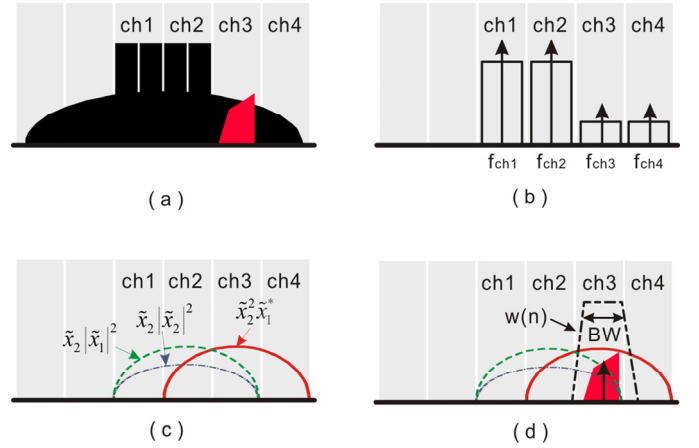


Fig. 2. The proposed method.(a) channelized output signal (2) channel arrangement (3) proposed channel basis (4) proposed method

For channel 3, the basis function is,

$$B_{1,\text{ch3}}(n) = \tilde{x}_1^*(n) \tilde{x}_2^2(n) \quad (3)$$

Since all the basis functions are generated at baseband and their center frequencies are at DC, additional frequency shift must be conducted to align them properly. For instance, the center frequency of the basis functions in channel 2 must be shifted left by one channel to align with that in channel 3. This operation can be achieved by introducing a phase shifting function $P(n)$. In this case, $f = f_{\text{ch3}}$

$$\begin{cases} P_{\text{ch2}}(n) = e^{j2\pi(f_{\text{ch2}}-f)nT} \\ P_{\text{ch3}}(n) = e^{j2\pi(f_{\text{ch3}}-f)nT} \end{cases} \quad (4)$$

As described in [4], higher order nonlinearities can be modeled by using a second basis function $B_2(n)$, which can be represented as

$$B_2(n) = \sqrt{|\tilde{x}_1(n)|^2 + |\tilde{x}_2(n)|^2} \quad (5)$$

Then, the total distortion in channel 3 can be formed as,

$$\tilde{y}^d(n) = \sum_{k \in \{\text{ch2}, \text{ch3}\}} \sum_{r=1}^R \sum_{m_1=0}^{M_1} \sum_{m_2=0}^{M_2} \sum_{p=0}^P c_{k,p,m_1,m_2}^{(r)} B_{1,k}^{(r)}(n - m_1) \cdot P_k(n) \{B_2(n - m_2)\}^p \quad (6)$$

where $B_{1,k}^{(r)}(n)$ is shown in (2)-(3), $P_k(n)$ is shown in(4), $B_2(n)$ is defined by (5), and $c_{k,p,m_1,m_2}^{(r)}$ are the coefficients

Since only the sideband distortion around the received band is required to be compensated as shown in Fig. 2d, it will be only part of the modeled distortion, leading to the issue of bandwidth mismatch. Therefore, the band-limited technique [5] could be employed to overcome this issue. From Fig. 2d, the band-limiting function can be designed with the BW of the

unwanted emission and the time domain representation can be denoted as $w(n)$. Therefore, the proposed model is

$$\hat{y}^d(n) = \sum_{k \in \{ch2, ch3\}} \sum_{r=1}^R \sum_{m_1=0}^{M_1} \sum_{m_2=0}^{M_2} \sum_{p=0}^P c_{k,p,m_1,m_2}^{(r)} B_{1,k}^{(r)}(n - m_1) \cdot P_k(n) \{B_2(n - m_2)\}^p \otimes w(n) \quad (7)$$

Although only the sideband distortion in channel 3 has been thoroughly discussed in this paper, the distortion falling in other channels can be easily constructed by following the similar procedures.

Because the original input has been channelized, the signal processing bandwidth will only depend on the channel bandwidth, instead of the original one. Thus the processing bandwidth for nonlinear term modeling will be reduced by half in this case. Also, compared to the filtering technique in [1], this operation can be realized in lower data rates. Due to these merits, the proposed model can effectively lead to low-complexity and low-cost designs. Meanwhile, due to the flexibility of the band-limiting function, the center frequency and bandwidth of the compensated area can be easily controlled.

III. MEASUREMENT RESULTS

A Q-band mmWave test bench was setup to validate the proposed model, as shown in Fig. 3. A 4-carrier 80 MHz input signal with peak-to-average power ratio (PAPR) of 7.5 dB was generated by the software Matlab in PA, then downloaded to the signal generator, up-converted to 40 GHz, and finally fed into a mmWave PA (HMC5929LS6), which is a 4-stage GaAs pHEMT MMIC PA with the output power of 16 dBm. In order to emulate the unwanted emission, a portion of the distortion signal will be coupler into the receiver chain and then filtered out to obtain the leaked sideband distortion. The model parameters are set as the nonlinear order $P = 1$ and the memory length M_1 and M_2 are simplified to the same value of 1. And the compensated bandwidth is varied from 30 MHz to 10 MHz to fully validate the idea. The overall number of the model coefficients is only 12.

The measured power spectral density with and without compensation is shown in Fig. 4. From Fig. 4, it can be seen that the sideband distortion can be successfully removed and more than 15 dB improvement can be achieved. Besides this,

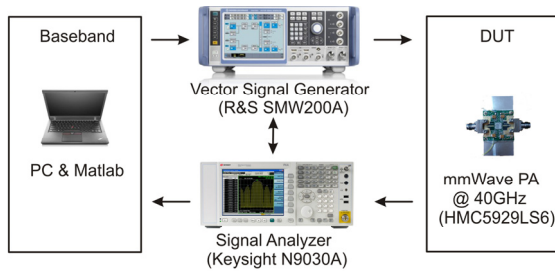


Fig. 3 Test bench setup.

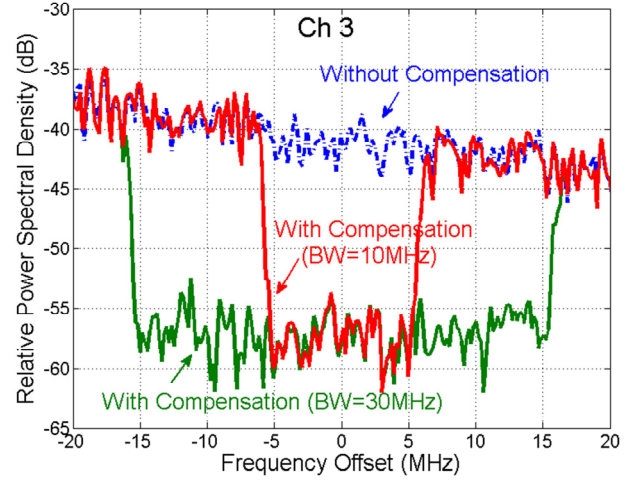


Fig. 4. Measured relative power spectral density (Channel 3).

the proposed method has the flexibility to control the compensation bandwidth around the center frequency of receiver band. Although the bandwidth is reduced, the compensation performance still keeps the same. This property will bring us a great advantage to adapt the receiver band change, which will be very useful in software defined radio.

IV. CONCLUSION

In this paper, a channelized sideband distortion model was proposed to successfully suppress the unwanted emission. By employing the proposed model, the unwanted emission can be effectively removed in the severe wideband contiguous carrier aggregation scenario. Agile control on center frequency and bandwidth of sideband distortion compensation will provide the system re-configurability which is vital in future communication systems. Also this method has the potential of extending it to smaller channels which will keep reducing the signal processing bandwidth.

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