Third-order passive intermodulation distortion cancellation using a cubic Volterra filter for wireless relay systems

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Abstract: Passive intermodulation distortion (PIMD) is a phenomenon in which two or more transmission signal frequencies interfere with each other due to non-linearity in passive elements of a wireless communication system and undesired signals are generated. Such intermodulation distortion increases the noise level in the receive frequency band of the wireless communication system, thereby degrading the performance of the receiver. In this paper, a PIMD mitigation scheme based on a modified cubic Volterra filter is proposed to reduce a passive intermodulation distortion level to enhance the uplink signal receive performance. The performance of the proposed approach is evaluated by applying it to the data sampled at a repeater for the long term evolution (LTE) system. The proposed approach demonstrates a notable reduction of PIMD in the receive band. The conventional least mean square (LMS) approach is considered in this study for the purpose of comparison.

Key Words: interference suppression, nonlinear components, passive intermodulation, cubic Volterra filter, wireless communication

1. Introduction

Passive intermodulation distortion (PIMD) is a distortion caused by the nonlinear mixing of two or more signals with different frequencies in a passive element. In the communication systems, the performance degradation due to this distortion has been observed variously. For carrier aggregation in the long-term evolution (LTE) cellular system, for example, the PIMD produced by multiple carriers occupies a relatively large spectrum resource and the resulting PIMD may appear in the uplink bands [1]. In this case, the reception performance of the base transceiver stations or the repeaters is significantly degraded for the uplink signal. In recent years, a variety of bands have been integrated into one RF circuit for sharing base stations and repeaters in order to increase the efficiency of system management [2, 3]. In this development, the occurrence of PIMD appears to be broadband and relatively high power, resulting in deterioration of system performance.

In the last decades, much research on PIMD has focused on phenomena, measurement techniques and mechanisms [4, 5]. To mitigate PIMD, a method of introducing artificial and adjustable passive
nonlinearities was considered [6], while an adaptive algorithm that removes nonlinear interference was proposed for a mobile inband full duplex radio and it was implemented using a software defined radio based on the graphics processing units [7]. Various real-time adaptive algorithms have been proposed to eliminate PIMD in digital satellite communication transceivers [8].

In this paper, an efficient PIMD mitigation algorithm is proposed for the repeaters in the LTE cellular communication system which transmits downlink signals in two different bands while receiving an uplink signal. The removal of third order PIMD components is carried out through an internal signal processing algorithm, in which the PIMD component is modeled with the third-order polynomial with memory characteristics, which is called a modified cubic Volterra filter [9].

This paper is organized as follows. In the following section, the problem formulation is carried out with the system and signal models considered in this study. In Section 3, details of the proposed approach are described and in Section 4, the conventional approach is briefly explained and the data measurement setup is described. The experiment results of the proposed approach are presented. Finally, concluding remarks and future research direction are given in Section 5.

2. System and signal models

The overview of the transmission/reception operations of a repeater in the cellular system considered in this study is shown in Fig. 1(a). It is assumed that the center frequencies of the downlink signals $TX_1$ and $TX_2$ are $f_1$ and $f_2$, ($f_1 < f_2$) and without loss of generality, the reception (uplink) band is located below the transmission band. In case that this reception band is placed above the transmission band, the two input components to the modified cubic Volterra filter employed to model the PIMD signal should be exchanged. The two downlink signals $TX_1$ and $TX_2$ are combined and sent to the shared antenna through the duplexer while the uplink signal received by the antenna is passed through the duplexer. The PIMD signal, which is generated by the downlink signals, is added to the uplink signal at the duplexer to produce the received signal.

The baseband complex representations of the downlink signals $TX_1$ and $TX_2$ are denoted by $x_1(n)$ and $x_2(n)$, respectively. The baseband signal model $y(n)$ for the received uplink signal with center frequency $f_{RX}$ is as follows.

$$y(n) = r(n) + p(n) + v(n),$$ (1)

where $r(n)$, $p(n)$ and $v(n)$ stand for the equivalent uplink signal, PIMD signal, and noise in baseband, respectively.

3. The proposed approach

The key idea of the proposed approach can be expressed as follows.

$$\hat{r}(n) = y(n) - \hat{p}(n),$$ (2)
where the signal $\hat{r}(n)$ is the estimated uplink signal while the signal $\hat{p}(n)$ represents the output from the model describing the nonlinear relationship between the third order PIMD $p(n)$ and the downlink signals $x_1(n)$ and $x_2(n)$.

When developing the model, it is assumed that the uplink signal $r(n)$ and the PIMD signal $p(n)$ are statistically independent. The proposed approach is summarized in Fig. 2. First the downlink signal $x_1(n)$ and $x_2(n)$ and the received signal $y(n)$ are applied to estimating the model. Note here that the signal used to estimate the model coefficients is not $p(n)$ but $y(n)$ because the PIMD signal $p(n)$ is not available while the repeater is in operation and it is independent of the uplink signal $r(n)$. Next, the model output is computed with the downlink signals and the estimated model coefficients. Finally, the uplink signal is estimated by subtracting the model output, the estimated PIMD from the received signal $y(n)$ as in (2).

![PIMD cancellation block diagram.](image)

To model PIMD $p(n)$ with the two downlink signals, the modified cubic Volterra filter [9] is employed. In this study, without loss of generality, the third-order PIMD located at the band of the center frequency $2f_1 - f_2$ is considered. This PIMD is generated from the passband signals having two different frequencies, which is modeled by complex conjugate of $x_1$ and $x_2$, while the other PIMD at $2f_2 - f_1$ can be generated from $x_1$ and conjugate of $x_2$ [10]. Using the two-input cubic Volterra filter with a memory length of $L - 1$, the modeled PIMD $\hat{p}(n)$ can be expressed as:

$$\hat{p}(n) = \sum_{k_1=0}^{L-1} \sum_{k_2=0}^{L-1} \sum_{k_3=0}^{L-1} h_c^{F}(k_1, k_2, k_3) \times x_1(n-k_1)x_1(n-k_2)x_2^*(n-k_3),$$

(3)

where $h_c^{F}(k_1, k_2, k_3)$ represents the filter coefficients and the superscript * represents the conjugate. Since the symmetry of $x_1(n-k_1)x_1(n-k_2) = x_1(n-k_2)x_1(n-k_1)$ is established in (3), it can be reduced to

$$\hat{p}(n) = \sum_{k_1=0}^{L-1} \sum_{k_2=0}^{L-1} \sum_{k_3=0}^{L-1} h_c(k_1, k_2, k_3) \times x_1(n-k_1)x_1(n-k_2)x_2^*(n-k_3),$$

(4)

where $h_c(k_1, k_2, k_3)$ represents the corresponding cubic Volterra filter coefficients for the reduced input components, noting that the time index $k_2$ start from $k_1$. The number of the coefficients $h_c^{F}(k_1, k_2, k_3)$ becomes $L^2(L+1)/2$ in (4) whereas that is $L^3$ in (3).

Equation (4) can be rewritten in vector form as follows.

$$\hat{p}(n) = h_c x_c(n),$$

(5)

where the coefficient vector $h_c$ is the $1 \times N$ row vector consisting of the coefficients $h_c(k_1, k_2, k_3)$ with $N = L^2(L+1)/2$, and the input vector $x_c(n)$ is an $N \times 1$ column vector consisting of elements $x_1(n-k_1)x_1(n-k_2)x_2^*(n-k_3)$.

The coefficient vector $h_c$ is estimated using the Wiener-Hopf equation [11]. To do this, (5) is rewritten for $K$ samples of the signal $\hat{p}(n)$ as follows.
\[ \hat{p} = h_c X_c, \]  

where \( \hat{p} \) is the 1 \( \times \) \( K \) row vector consisting of \( \hat{p}(n) \). On the other hand, the \( N \times K \) matrix \( X_c \) consists of the vectors \( x_c(n), n = 0 \ldots K - 1 \). Thus, the estimation of \( h_c \) is carried out by computing the following equation.

\[ h_c = \hat{p}X_c^H (X_cX_c^H)^{-1}, \]  

where the superscript \( H \) represents the Hermitian operation on a matrix. Note that the matrix \( X_cX_c^H \) has its inverse when \( K \) is sufficiently greater than \( N \).

There is no way to separate the PIMD signal from the received signal while a repeater transmits and receives. As shown in (1), the signal \( y(n) \) is received as a mixed signal of the uplink signal \( r(n) \) and the PIMD \( p(n) \). In this study, it is assumed that the uplink signal \( r(n) \) is statistically independent of the PIMD signal \( p(n) \). Thus, the vector \( \hat{p} \) in (7) is constructed as the received signal \( y(n) \) instead of \( p(n) \). The estimated coefficient \( h_c \) is applied to (5) to obtain \( \hat{p}(n) \). Finally, using (2), the uplink signal is obtained as \( \hat{r}(n) \).

4. Experimental results

4.1 Conventional approach based on least mean square

In this subsection, for the purpose of comparison, the conventional approach scheme is applied to the same data. The conventional approach relies on the complex least mean square (LMS) algorithm [11, 12], which is employed for estimating the relationship between the inputs \( x(n) \) and the actual PIMD \( p(n) \). The operation of the conventional approach can be described by the following equation.

\[ \hat{p}(n) = \hat{w}^H(n)u(n), \]  

where the input vector \( u(n) = [x_2^1(n)x_2^2(n), x_2^1(n - 1)x_2^2(n - 1), \ldots, x_2^1(n + K - 1)x_2^2(n + K - 1)]^T \) consists of the input samples, \( \hat{p}(n) \) is the estimated PIMD samples and the vector \( \hat{w} \) represents the filter coefficients. The error sample \( e(n) \) is obtained by

\[ e(n) = p(n) - \hat{p}(n), \]  

Note that the present error sample \( e(n) \) is used to update the filter coefficients \( \hat{w}(n + 1) \) as follows.

\[ \hat{w}(n + 1) = \hat{w}(n) + \mu u(n)e(n)^*, \]  

where \( \mu \) represents the step size of the LMS filter and the superscript * denotes complex conjugate. The optimized filter coefficients are used to predict PIMD.

4.2 Data measurement environment

The block diagram of the wireless repeater system considered in this study is shown in Fig. 3. In Fig. 3, the block denoted by RDTU represents the slave digital transceiver unit of remote repeater, the PA.
block denotes the power amplifier, the PCU block is the passive intermodulation capture unit, which is used to capture both transmit data and third order PIMD data. The downlink baseband signals are generated by Keysight signal generators N5082B while the Keysight signal analyzer N9020A is used for converting RF data to digital baseband data and the TELCON 2-way power divider is used for power dividing in the repeater. The measurement setup is shown in Fig. 4.

4.3 Results

In this section, the performance of the proposed scheme is evaluated from the point of view of the normalized mean squared error (NMSE) using the data set obtained from the repeater for the LTE cellular system [13]. NMSE is defined as follows.

$$\text{NMSE} = \frac{1}{K} \sum_{k=0}^{K-1} \left| r(k) - \hat{r}(k) \right|^2, \quad (11)$$

where $r(k)$ is the uplink signal without the effect of the PIMD, while $\hat{r}(k)$ is the estimated uplink signal from the received signal, which is affected by PIMD. The parameter $K$ is the number of samples used in the evaluation.

The data set consists of two downlink, one uplink and one PIMD signals, each of 22500000 samples, which are sampled with a rate of 45 MHz. In the repeater, the downlink LTE signals at $f_1 = 2135 \text{ MHz}$ and $f_2 = 2322.5 \text{ MHz}$ are shifted to the IF band and sampled and converted to the complex baseband. The spectra of the two downlink signals are plotted in Figs. 5(a) and (b), respectively. The spectrum shown in Fig. 5(c), is that of the uplink signal affected by the PIMD.

The received signal in Fig. 5(c) is processed by the proposed approach with $L = 2$ and the conventional approach with $L = 17$ to obtain the estimated uplink signal, whose spectra are displayed in Fig. 5(d). Note in the figure that the frequency components out of band are notably suppressed compared to that in Fig. 5(c). NMSE of the proposed approach is $-29.21 \text{ dB}$ while that of the conventional approach is $-25.69 \text{ dB}$.

When applying both the proposed and conventional approaches for mitigating the PIMD from the received signal using the downlink signals, the memory length and the time mismatch between the downlink signals and the PIMD are very critical to the performance of both the approaches. In order to investigate the effect of the memory length, NMSE’s between the true and estimated uplink signals are measured for the memory lengths from 0 to 8, and they are plotted in Fig. 6(a). As observed in the figure, the minimum NMSE of proposed approach is achieved at the length of $L - 1 = 1$, which
Fig. 5.  (a) Spectrum of the downlink signal Tx1 centered at $f_1 = 2135$ MHz.  
(b) Spectrum of the downlink signal Tx2 centered at $f_2 = 2322.5$ MHz.  
(c) Spectrum of the passive intermodulation $p(n)$ centered at $F_{IM} = 1947.5$ MHz.  
(d) Spectra of the estimated uplink signal by the proposed approach and the conventional one (the red line represents the spectrum obtained by the proposed while the black line does that by the conventional one).

implies that the size of the coefficient vector $h_c$ is $1 \times 6$. As the memory length $L - 1$ increases, the NMSE of the conventional approach slowly decreases, but its performance is worse than that of the proposed approach. Note that the memory length of $L - 1 = 1$ observed in this experiment is not a fixed value because it is dependent on many experimental variables including the length of the circuit.
path, the type of the passive device and so on. Thus, the automatic or manual estimation scheme is required.

Next, the cancellation performance is observed according to the time mismatch between the downlink and PIMD signals. In this experiment, NMSE’s are measured for the time mismatches from −5 to 5 samples, which is displayed in Fig. 6(b). As observed in the figure, the performance of both the approaches suddenly degrade beyond ± 2 samples.

5. Conclusion
In this paper, a method of mitigating PIMD is proposed for the repeater in the LTE cellular system. In this development, the modified two-input cubic Volterra filter is employed to model the PIMD signal using the downlink signals of two different bands and the filter output is applied to the received signal to estimate the uplink signal. In this study, it is assumed that the uplink signal and the PIMD signal are independent of each other. The performance of the proposed approach is evaluated using the downlink, uplink and PIMD signals sampled in the repeater. For comparison purposes, the LMS based iterative approach is employed as a conventional approach. The experiment results demonstrated that the proposed approach is superior to the conventional one. In terms of NMSE, the performance is evaluated for the memory length and the time mismatch. The spectrum of the recovered uplink signal from the received signal is demonstrated compared to that of the received signal, which is contaminated by the PIMD. Since the proposed scheme is carried out relying on the block process, there is a delay problem in that the estimated uplink signal is output in a predetermined block unit. An adaptive or recursive implementation of the proposed approach should be developed for practical applications.

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