Adaptive Tx Skirt Suppression for Multi-Radio In-Device Coexistence

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***Abstract*—With the proliferation of multi-standard mobile devices, in-device coexistence (IDC) has become a key challenge in the design of modern radios. Typical IDC use cases involve radio transmitters (aggressors) that are interfering with radio receivers (victims) collocated on the same device. Isolation of the sensitive receiver from high power transmitters on the same device poses major difficulties due to insufficient frequency separation between the aggressors and their victims. In this paper, we present an adaptive approach to suppress unwanted out-of-band signal power (i.e. TX skirt)from the aggressor to minimize desensitization at the victim. The proposed method relaxes off-chip filtering requirements and reduces guard band spacing, leading to a low cost integrated solution for multi-standard radios. To highlight the effectiveness of the proposed algorithm, we have demonstrated greater than 30 dB improvement in signal-to-interference ratio (SIR) enabling the coexistence between Band-40 LTE and 2.4GHz Wi-Fi radios on the same device.**

I. Introduction

With increasing demand for added functionality in smart phones with extremely small form factors, the support of multiple radio standards on the same device becomes essential. Multiple radios could operate concurrently and interfere with one another. For example, to talk while the phone also serves as a mobile hotspot, the LTE and Wi-Fi radios must operate simultaneously. Isolation on chip or even on a printed circuit board is not sufficient to isolate the LTE receiver from the Wi-Fi transmitter. In the above scenario the interfering transmitter and the un-intended receiver is usually referred to as the aggressor and the victim, respectively. The interfering transmitter power that couples to the un-intended receiver front-end consists of two major components. The portion of power centered around the transmitter carrier frequency is referred to as the Tx leakage, and the portion centered around the receiver carrier frequency is referred to as the Tx skirt. Tx leakage results in severe nonlinearity in receiver frontend. Tx skirt is the result of noise power from the output of a power amplifier (PA). When a receiver operates nearby the transmitter frequency, the power of Tx skirt overwhelms the desired receive signal. In this paper, We will use 2.4GHz Wi-Fi transmission and Band-40 LTE reception to illustrate our proposed scheme. It should be noted, however, that the proposed algorithm can easily extend to other IDC scenarios.

Traditionally, time duplexing in the MAC layer has been used to enable IDC by disabling Wi-Fi transmissions when LTE is receiving or by blocking off channels that are near the edges of the Wi-Fi transmission band. However, throughput suffers due to reduced frequency channels or limited time slots that could be shared. Therefore, solutions in the physical layer that maximizes throughput are more desirable. In [1], the author proposed a method to generate an active notch at the receiver frequency in the PA driver impedance. It equivalently creates a notch to attenuate the Tx skirt in the receiver band. Due to imprecision of analog implementations, this technique can only reduce Tx skirt by about 20 dB. Our approach leverages digital signal processing to achieve greater amount of Tx skirt suppression (e.g. 30dB). Based on an adaptive algorithm, our approach allows the suppression to occur in the background without interrupting normal signal reception. The major challenge of adaptive Tx skirt cancelation is in obtaining a clean reference signal as required by adaptive noise cancelation (ANC) schemes [2]. However, in most IDC scenarios this clean reference is not available because of cross-talk among multiple receiving paths. The obvious way to handling crosstalk is to introduce an extra clean copy of reference signal [3]. However, a clean reference signal is not available in most applications. While blind approaches could be used [4], they are limited by the special requirements, such as, the spectrum shape of the aggressor and victim.

In this paper, an adaptive Tx skirt suppression scheme is proposed for a two-path receiver, where the reference path is based on either one of the diversity receiver or from the introduction of an auxiliary path. Here we illustrate our concept on an LTE receiver that employs two diversity antennas. For receivers with no diversity antennas, an auxiliary path receiver [5] can be used. By taking advantage of the known transmitted signal, the proposed algorithm estimates the Tx skirt using a combined polynomial and channel model. The estimated signal serves as a clean reference signal for adaptive cancelation. The rest of the paper is organized as follows. Section II describes the adaptive Tx-skirt cancelation algorithm and Section III reports experimental results.

II. Adaptive Tx Skirt Suppression

Tx skirt comprises of an inter-modulation term (IM) and a noise term (Fig. 1(a)). The relative strength between these two terms depends on the frequency spacing between the transmitting band and the receiving band. For close-in bands, the IM term dominates while for faraway bands the noise term dominates. While it is possible to train a parametric model that estimates the IM portion of the Tx skirt with priori

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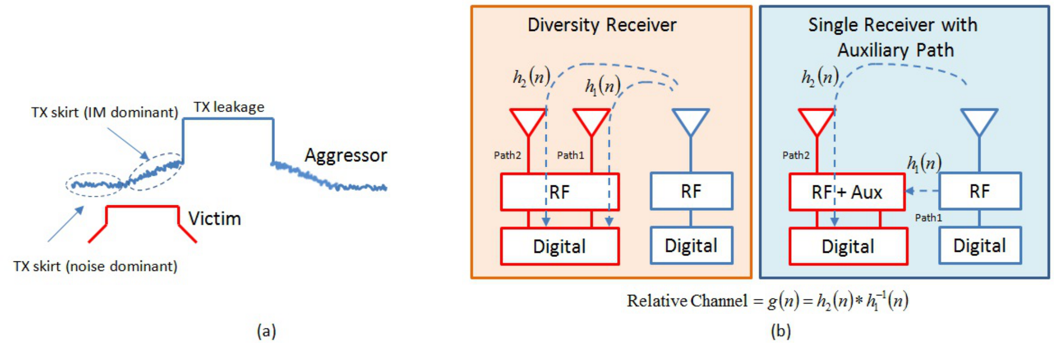

Fig. 1. (a) Tx skirt impairment (b) Concept of Tx skirt suppression for a diversity receiver and a single receiver w/auxiliary path. Note that the auxiliary path can also be used with a diversity receiver to achieve noise cancelation while maintaining the diversity gain.

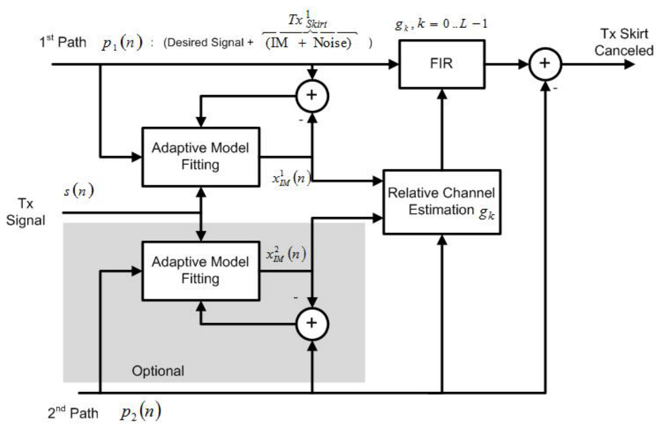

Fig. 2. Adaptive Tx Skirt Suppression (Relative channel estimation is to estimate relative Tx skirt channel g_k such that $Tx^2_{Skirt} = Tx^1_{Skirt} * g_k$)

knowledge of the transmitted signal, the noise term cannot be predicted. The proposed algorithm overcomes this limitation by utilizing two receiving paths to cancel both the IM and noise terms within the Tx skirt. Fig. 1(b) shows the system block diagram for the case with a two-path diversity receiver (e.g. LTE with dual antenna diversity), as well as, the case with one receiver with an auxiliary receiving path [5]. In this paper, LTE with dual-antenna diversity will be used to illustrate the effectiveness of the Tx-skirt cancelation algorithm.

Because of path differences between the Wi-Fi transmitter and the two LTE receivers, there exists a relative response between the two paths denoted by g_k. This relative channel represents the difference between Tx skirts observed on the two paths, h_1 and h_2. The proposed adaptive algorithm estimates g_k to align the two paths so that the Tx skirt from path 1 can be employed to cancel the Tx skirt in path 2. The traditional ANC cannot be directly applied because a ”clean” reference signal which contains only the Tx skirt is unavailable. This is because the LTE signal appears with the Tx skirt on both receiver paths. Note that even for the case with one receiving path, the auxiliary path gets corrupted by leakage from path 2 due to imperfect isolation. The LTE signal produces an unwanted correlation term that corrupts the correlation from the Tx skirts, compromising the optimal solution achieved by traditional ANC algorithms. To overcome this limitation, our proposed algorithm eliminates the unwanted correlation term by utilizing prior knowledge of the Tx signal to extract the IM part of the Tx skirt from path 1. This extracted IM term can then be used to determine the coefficient of g_k. Since the extracted IM is uncorrelated with the desired signal and noise terms in path 2, their correlations do not corrupt the optimal solution. Moreover, since both the noise and IM components of the Tx skirt pass through the same set of components between the Wi-Fi transmitter and the LTE receiver and have nearly the same bandwidth, the optimum coefficients found for g_k can also be used for the cancelation of the noise component in the Tx skirt.

A. System Diagram

Fig. 2 shows a detailed block diagram of the proposed algorithm which is implemented by two adaptive loops. The adaptive model fitting loop estimates and tracks the IM portions (x^1_{IM} and x^2_{IM}) of the TX skirt for path 1 and path 2, respectively. IM1 and IM2 are used in the relative channel estimation loop to determine the optimum coefficients for g_k. Since the IMs only contain information about Tx skirt and is independent to the desired signal, it can effectively drive the relative channel estimation block to the optimum coefficient values for g_k such that when the second path is subtracted from the output of the FIR filter, the Tx skirt is canceled. Conceptually, a model fitting module should be used for each path to isolate IMs. However, it can be shown that the model fitting of the second path is optional because x^1_{IM} is uncorrelated with the desired signal and noise in the second path. Therefore, omitting model fitting in path 2 does not affect the steady state response of the adaptive cancelation. The merit of the optional fitting loop lies in the fact it can speed up convergence when signals with high power (e.g. $>$ -70dBm) arrives at the LTE receiver inputs.

B. Adaptive Model Fitting

The Tx skirt model consists of an IM portion and a noise portion as illustrate in Fig. 3. The IM distortion arises primarily from nonlinearity in the PA, as well as, the filter response from the transmitter to the receiver. Modeling the in-band nonlinearity of the PA is a complex topic and has been discussed extensively in [6]. IM modeling of the Tx skirt

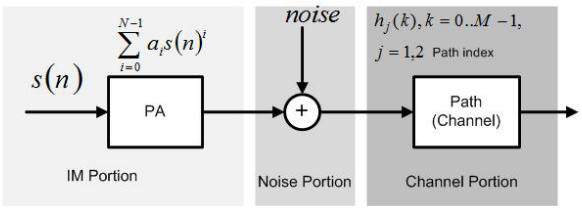

Fig. 3. Tx Skirt Model

is even more complicated because the skirt is the combined result of PA nonlinearity and channel distortion. Note that the proposed model is an approximation because convolution cannot be interchanged with nonlinear polynomial operation, and the response before and after the PA cannot be lumped into a single channel model. Fortunately, the purpose of the model fitting is not to directly use the IM estimates precisely for cancelation but to provide a clean reference signal to drive the relative channel estimation loop. Therefore, the Tx skirt modeling does not have to be precise, and the approximation is sufficiently accurate when there is one dominant power in the polynomial which is usually the case.

The IM portion of the Tx skirt on the j-th path is modeled as

$$x_{IM}^{j}(n) = \sum_{k=0}^{M-1} (\sum_{i=0}^{N-1} a_i s(k)^i) h_j(n-k) \tag{1}$$

Here a_i is the i-th the polynomial coefficient, N is the order of the polynomial. $h_j(k)$ is k-th tap coefficient of the FIR filter for the j-th path, and M is the length of the FIR. The values of the polynomial coefficients a_i can vary depending on the signal level $s(k)$. The objective of model fitting is to find the parameters a_i and $h(k)$ to minimize the following function for path 1.

$$J_1 = E\{(p_1(n) - x_{IM}^1(n))^2\} \tag{2}$$

where $p_1(n)$ represents the current waveform observed in the first path and E is the statistical expectation operator. The derivative of J_1 with respective to a_i is

$$\frac{\partial J_1}{\partial a_i} = 2E\{(p_1(n) - x_{IM}^1(n))(\sum_{k=0}^{M-1} s(k)^i h_1(n-k))\} \tag{3}$$

and the derivation of J with respective to $h(k)$ is

$$\frac{\partial J_1}{\partial h_1(k)} = 2E\{(p_1(n) - x_{IM}^1(n))(\sum_{i=0}^{N-1} a_i s(n-k)^i)\} \tag{4}$$

Eqn. 3 and 4 form the basis for the parameter update in the model fitting loops shown in Fig. 2. Similar derivation can be applied to obtain the coefficient update for path 2 by changing the corresponding indices to 2.

C. Relative Channel Estimation

The relative channel from the first path to the second path is denoted by g_k. For proper cancelation, g_k is the parameter that minimizes the following objective function

$$J_2 = E\{(p_2(n) - \sum_{k=0}^{L-1} x_{IM}^1(n-k) g_k)^2\} \tag{5}$$

where $p_2(n)$ is the waveform in the second path and x_{IM}^1 is the estimation of the IM portion of the Tx skirt in the first path. g_k is the k-th coefficient of an L-tap FIR filter. The optimization of this objective function is to determine filter coefficients that match path 1 to path 2 for effective cancelation. The adaptive update method is easily obtained by taking the derivative of the objective function as shown below

$$\frac{\partial J_2}{\partial g_k} = 2E\{(p_2(n) - \sum_{j=0}^{L-1} x_{IM}^1(n-j) g_j) x_{IM}^1(n-k)\} \tag{6}$$

The expectation operator can be removed which leads to the well-known least mean square (LMS) algorithm for simple implementation. The derivation can be extended to the case in which the optional model fitting is implemented for the second path. The $p_2(n)$ in Eqn. 5 needs to be replaced by the estimation of the IM portion x_{IM}^2. Optional model fitting in path 2 smoothes the suppression when the LMS algorithm is adopted, because the adjustment of g_k will not be affected by the signal or noise component of Tx skirt in path 2.

The most important property of the proposed algorithm is the separation of the interfering signal correlation from correlation of the desired signal. This is achieved through Tx skirt fitting, which can be viewed as a special type of ”filtering”. Intuitively, it can be viewed as a orthogonal projection onto a subspace spanned by the bases learned from Tx skirt fitting, which removes the signal components and leaves only the Tx skirts. The dual-loop adaptive algorithm simultaneously updates the bases for the Tx skirt subspace and converges to the optimum coefficients g_k to cancel not only the IM part but also the noise part of the Tx skirt. Since the purpose of projecting to subspace is to eliminate the influence of the desired signal and set the right direction for updating g_k, it is possible to project to part of Tx skirt subspace. This means the accurate modeling of Tx skirt IM is not necessary because part of IM is enough to drive the adaptive loop to the right direction although at a slower rate.

III. Experiments

This section demonstrates the effectiveness of the proposed algorithm in an IDC scenario with Wi-Fi being the aggressor and B40 LTE being the victim. Fig. 4 illustrates the cancelation performance with different orders of polynomial skirt fitting. In this experiment, the desired signal, IM and noise portion of the Tx skirt have the same power level. The step size for model fitting and skirt cancelation are 0.01 and 0.001, respectively. ANC can only achieve 10 dB suppression because of the crosstalk of LTE signals. With model fitting, this crosstalk is removed and 30 dB cancelation can be achieved. With the order of PA nonlinearity set to seven, 3rd, 5th and 7th order polynomials are tested for model fitting. All cases successfully drive the adaptive filter to achieve 30 dB suppression of Tx skirt, the 7th order model achieving with the shortest convergence time. This phenomenon confirms that it is not necessary to predict the skirt precisely as long as it captures the correct correlation of the Tx skirts. Note that capturing only

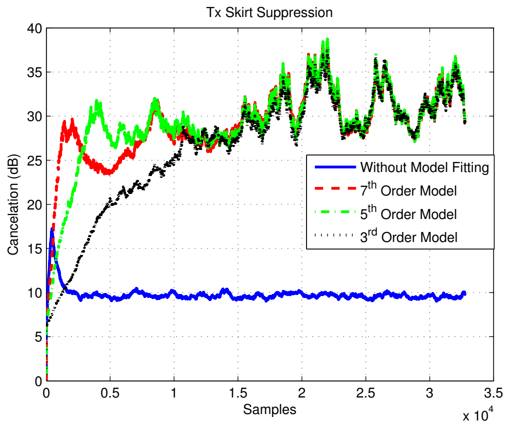

Fig. 4. Tx skirt suppression with/without model fitting

part of the correlation can potentially increase the convergence time, e.g., the 3rd order model converges the slowest.

Since the Wi-Fi transmitter and the LTE receiver are col-located in the same device, it is assumed that the relative channel between the aggressor and its victim is AWGN. The interference-to-signal ratio (ISR) is defined as the ratio between the total Tx skirt power and the LTE signal power. It is set to 15 dB for the first path and 10 dB for the second path. The main simulation parameters are based on the LTE specifications [7]. The step sizes for model fitting and skirt channel estimation are chosen as 0.01 and 0.001 respectively. Fig. 5(a) illustrates the learning curves of the proposed algorithms, averaged over 200 independent runs with a signal-to-noise ratio (SNR) of 2 dB. MSE_{model} denotes the mean square error (MSE) between the estimated x^1_{IM} model parameter and the ground truth parameters, and MSE_{FIR} represents MSE between the second path Tx skirt and the estimated one using the first path as a reference. The converged values of MSE_{model} and MSE_{FIR} are about -14 dB and -35 dB. The difference between the two MSEs also verifies that the model fitting does not have to be accurate for successful skirt cancelation. In order to further characterize the impact of the proposed algorithm at the system level, we implemented the proposed algorithm in an LTE platform to demonstrate the link-level performance. The result of packet error rate (PER) shown in Fig. 5(b) confirms that the Tx skirt can be successfully removed and the PER performance approaches that of an ideal one-path receiver with no Tx skirt interference. Fig. 5(b) also clearly shows that without Tx skirt cancelation the LTE receiver becomes useless as nearly all packets are in error, and with an auxiliary path it can achieve the receiving diversity and Tx skirt suppression simultaneously in a two path diversity LTE receiver.

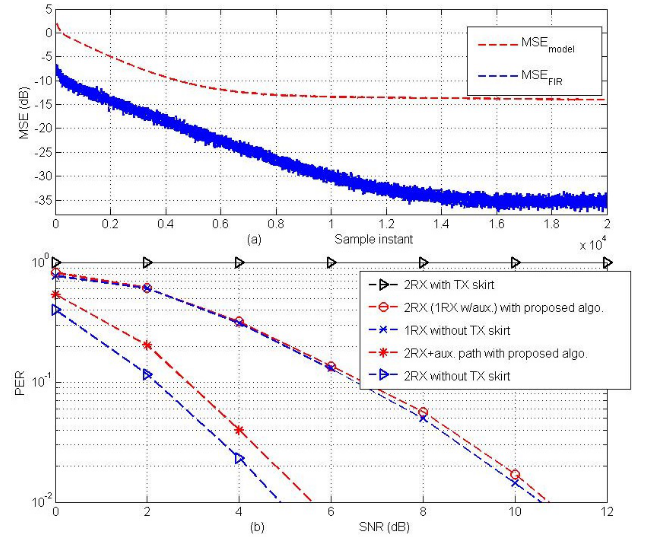

Fig. 5. (a) Learning curves (b) LTE PER performance with Wi-Fi interference

IV. Conclusion

This paper addresses the problem of Tx skirt in IDC and more specifically illustrates for the case of a 2.4 GHz Wi-Fi aggressor to an LTE victim operating in band 40. A dual-loop adaptive algorithm is proposed for a two path receiver architecture whereby the model fitting loop estimates the IM distortion component of the Tx skirt while the relative channel estimation loop adapts an FIR filter to achieve greater than 30 dB of suppression. Tx skirt fitting in the model fitting loop prevents the correlation from the desired signal to degrade the performance of the channel estimation loop. The main feature of the proposed algorithm is that it solves the crosstalk problem which degrades the performance of ANC. Furthermore, the high Tx skirt suppression does not require a precise model fitting of the Tx skirt IM distortion. Simulation results show that greater than 30 dB Tx skirt suppression can be achieved, leading to a reduction in guard band and reduced cost in discrete filters. Although the paper only discusses Tx skirt suppression in a two-path receiver, a straightforward extension leads to a general M-path receiver which can achieve M-1 path receiving diversity after Tx skirt suppression. To maintain the M-path diversity gain and to handle cases with no diversity receiver, an auxiliary receiver can be used.

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