TX Leakage Cancellation with Adaptive Delay Filter

Han Su, Grzegorz Szczepkowski, and Ronan Farrell

***Abstract*—In an Frequency-Division Duplexing (FDD) transceiver, a high power transmitted signal can leak into the RX chain due to limited isolation of a duplexer. Such signal is known as TX leakage and can seriously affect the performance of the receiver. A transmitter leakage canceller structure is proposed in this paper in order to improve isolation between the transmitter and receiver. The simulations show the proposed structure increases the isolation of a Surface Acoustic Wave (SAW) duplexer by more than 25 dB in 20 MHz bandwidth.**

***Index Terms*—Leakage cancellation, full duplex radios, FDD**

I. INTRODUCTION

FREQUENCY–DIVISION Duplexing (FDD) is widely used in modern wireless communication systems in order to transmit and receive signals simultaneously. A duplexer is used to separate the transmitted (TX) and received (RX) signal paths. It is desirable for industries to replace the bulky and expensive cavity duplexers with more compact and inexpensive ceramic or SAW devices. The difficulty is that the latter cannot provide as high isolation performance. Hence, the high power TX signal leaks into receiving chain in which case the performance of the receiver is seriously affected. Such high power signal in the RX chain is known as transmitter leakage (TX leakage) and consists of in-band and out-of-band components in respect to the RX signal.

To date, many various methods of TX leakage reduction have been published [1]-[5]. The method published in [1] tries to suppress the leakage in base band. Since the reference signal is taken from TX baseband, it doesn't contain information about high order distortion that is caused by the Power Amplifier (PA). Hence, it will not help to reduce the in-band TX leakage. Additionally, the leakage could saturate the RF front-end before reaching the canceller at baseband.

Another method proposed in [2] relies on LMS adaptive filter to cancel the out-of-band TX leakage. This method consists of four mixers and as a result, the noise levels increase significantly. Furthermore, the bandwidth is only 2 MHz with approximately 15 dB cancellation in the case of a SAW duplexer.

Auxiliary paths (or taps) with attenuators and delays are used in [3] and [4] to cancel a narrow band TX leakage. They all use a circulator as their duplexing device. A circulator can only provide relatively low isolation between TX and RX. More importantly a circulator has a wide pass band (consider it as an all-pass filter between adjacent ports following the circulation direction). Without additional band-pass filters, it is not possible to protect the RX chain from the external out-of-band interferences. When the circulator is replaced with a standard duplexer, the cancellation performance can no longer be guaranteed. The reason for it is that the flat magnitude response and linear phase response of the circulator are much simpler to be matched with no more than two taps. The characteristics of a duplexer are much more complex, consisting of pass bands, sharp transient bands and attenuation bands with deep nulls. In the case of the reported methods, it is easy to reduce the leakage at one frequency for a standard duplexer, but not over a wide bandwidth.

In [5], a larger number of taps is used and high cancellation performance has been reported. The method treats the circulator as a black box and only propagation delay is approximately known. However, the taps are not used efficiently. If this black box is characterized in terms of phase and magnitude response, the number of taps can be reduced to provide the same cancellation performance, or better performance can be achieved with the same number of taps.

The original system identification method using adaptive delay filter was proposed in [6] but only for baseband signal processing and it's purely digital. This paper proposes a TX leakage cancellation method also using adaptive delay filter, but operated at RF. This method can be successfully used for both in-band and out-of-band TX leakage, and therefore it has a potential for wide band cancellation. The outline of this paper is as follows: Section II discusses the proposed TX leakage cancellation structure. Section III focuses on the basic concept of the proposed structure. Section IV shows the simulation results. Finally, Section V is the conclusion.

II. PROPOSED TX LEAKAGE CANCELLER STRUCTURE

The adaptive delay TX leakage canceller shown in Fig. 1 consists of two main parts: estimation of delays and adaptation of coefficients. The estimation of delays is operated off-line, i.e., with no received signal presented. Delay values and tap weights (d_i and w_i where i is the tap number, $i = 1, 2, 3, \ldots, M$) are calculated sequentially. That is, the delay and weight of a later tap will not be calculated until the previous taps have been finished. For each tap, the estimation of delay and adaptation of tap weight are performed separately. For instance, in tap $i = 1$, the delay value is estimated first, following with the adaptation of the corresponding tap weight. After the values of the elements in the tap are determined, a new desired signal (the difference between the TX leakage

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and the reconstructed signal in this tap) is then obtained. The estimation and adaption for the subsequent taps are based on the new error signal generated by the previous steps. In physical realization, the weights w_1 to w_M are variable attenuators and d_1 to d_M are tunable delay lines.

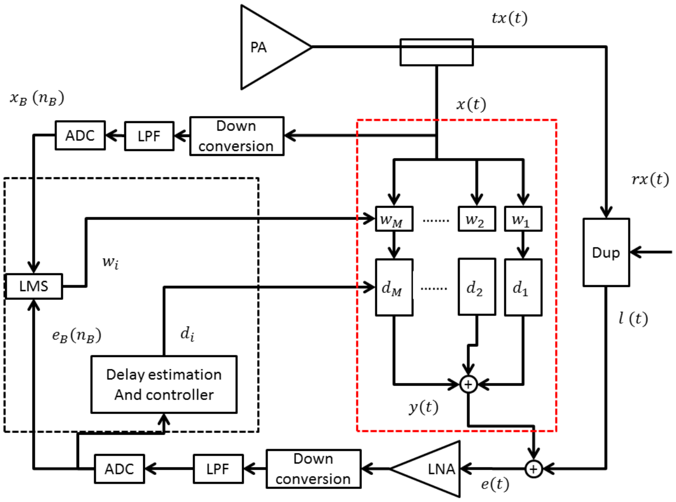

Fig. 1. Proposed structure of TX leakage canceller with adaptive delay filter

When the estimation of delays has been completed for all the available taps, the canceller can then be used on-line, i.e., with received signal being added in. At this time, delays are fixed and weights are jointly adapted based on the error signal at the baseband of the receiver.

The adaptation of tap weights can be achieved with any adaptive filter method. In this paper, Normalized Least Mean Squares (NLMS) method is used in the simulation for its low complexity and computation requirements.

III. ESTIMATION OF DELAYS AND ADAPTATION OF TAP WEIGHTS

Assume the RF signal is sampled and the sampling time is t_{sRF}. There is a ratio between the baseband sampling time t_{sB} and t_{sRF}.That is:

$$r = \frac{t_{sB}}{t_{sRF}} \tag{1}$$

Let D_i be the sample delay at RF for each tap i. The actual RF delay is then:

$$d_i = D_i \cdot t_{sRF} \tag{2}$$

A. *Estimation of delays*

The delay of each tap at RF is estimated at baseband in two steps. Firstly, coarse estimation is done by performing cross-correlation between the baseband error signal before being cancelled by the current tap ($e_{pB}(n_B)$) and the baseband reference signal ($x_B(n_B)$):

$$R_{x_B e_{pB}}(d) = x_B(n_B) \star e_{pB}(n_B) \tag{3}$$

where n_B is the baseband discrete time index. The estimated sample delay for tap i at baseband, D_{iB}, is the one which maximizes the absolute value of the correlation. Then the true sample delay at RF, D_i, is in the range of

$$\begin{cases} 0 \le D_i \le \left\lfloor \frac{r}{2} \right\rfloor, & D_{iB} = 0 \\ r \cdot D_{iB} - \left\lfloor \frac{r}{2} \right\rfloor < D_i \le r \cdot D_{iB} + \left\lfloor \frac{r}{2} \right\rfloor, & D_{iB} \neq 0 \end{cases} \tag{4}$$

where $\lfloor * \rfloor$ is the floor operator. A series of trial delays, D_{trial}, which have every possible value of D_i with known D_{iB} are used to determine the actual value of D_i. That is:

$$\begin{cases} D_{trial} = [0, 1, ..., \frac{r}{2}], & D_{iB} = 0 \\ D_{trial} = [r \cdot D_{iB} - \left\lfloor \frac{r}{2} \right\rfloor + 1, & \\ \qquad r \cdot D_{iB} - \left\lfloor \frac{r}{2} \right\rfloor + 2, & \\ \qquad ..., r \cdot D_{iB} + \left\lfloor \frac{r}{2} \right\rfloor], & D_{iB} \neq 0 \end{cases} \tag{5}$$

For each value of D_{trial}, a phase and delay compensated baseband reference signal must be obtained:

$$\hat{x}_B(n_B) = x_B(n_B - D_{iB}) \cdot e^{-j2\pi f_c D_{trial}(p) t_{sRF}} \tag{6}$$

where $x_B(n_B - D_{iB})$ is the delayed reference signal at baseband without compensating the phase. f_c is the centre frequency of the band of interest. p is the trial delay index. Then cross-correlation should be performed as:

$$R_{\hat{x}_B e_{pB}} = \hat{x}_B(n_B) \star e_{pB}(n_B) \tag{7}$$

For each value of $D_{trial}(p)$, a point which has the maximum absolute value of $R_{\hat{x}_B e_{pB}}$is recorded. An array $R(p)$ is formed with these points. The sample delay at RF, D_i is equal to $D_{trial}(int)$ so that the phase of $R(int)$ is the closest to either 0° or 180°of all $R(p)$.

B. *Adaptation of tap weights*

Once the delay at RF for a particular tap is determined, the weight can be adapted by using NLMS method. The adaptation controller is at baseband. Hence, complex NLMS adaptation equations should be used. However, some modifications need to be carried out on the standard equations before they can be used in the proposed structure. The baseband reference signal should be changed to:

$$x_{iB}(n_B) = x_B(n_B - D_{iB}) \cdot e^{-j2\pi f_c D_i t_{sRF}} \tag{8}$$

Then the NMLS adaptation equations are:

$$e_B(n_B) = e_{pB}(n_B) - w_i \cdot x_{iB}(n_B) \tag{9}$$

$$w_i = w_i + \frac{\mu \cdot real(x_{iB}(n_B) \cdot e_B^H(n_B))}{\left\| x_{iB}(n_B) \right\|^2} \tag{10}$$

where $e_B(n_B)$ is the new desired signal for next tap.μ is the step size of the NLMS algorithm.

IV. SIMULATION RESULTS

The duplexer model in the simulation is based on the S-parameters measurements of a W-CDMA band VIII SAW duplexer [7] with a balun [8] for converting the balanced ports of RX into single ended un-balanced port. S-parameters are measured with a Vector Network Analyzer. Interpolation of the S-parameters is performed to obtain frequency response information that is outside of the available frequency points in the measurements. The components were mounted on an FR-4 substrate with required matching circuits. The measured leakage characteristics are shown in Fig. 2 and Fig. 3.

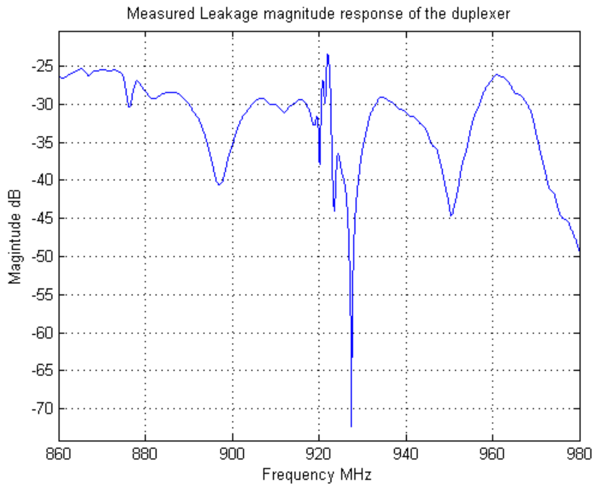

Fig. 2. Measured leakage magnitude response of the duplexer

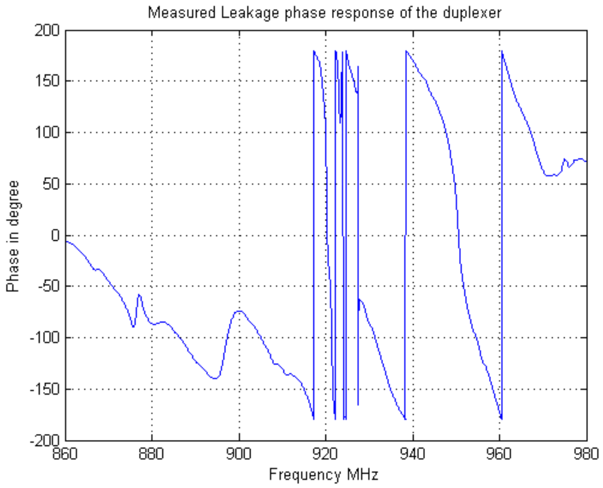

Fig. 3. Measured leakage phase response of the duplexer

Simulations are performed in Matlab. The sampling frequency used in the simulations is 4.96 GHz and the total number of points is 131072. The step size of the NLMS algorithm is set to 0.2. The baseband sampling rate is chosen to be 512 MHz. White Gaussian noise is used as the TX signal at RF and reference signal is set to be equal to the TX signal. Baseband signals are band-limited by low-pass filters. The simulation results in Fig. 4 and Fig. 5 show the leakage level within the band from 880 to 900 MHz when the canceller is on and off. The numbers of taps is 8 and 16 respectively and average cancellation performance is approximately 25 dB and 30 dB accordingly over 20 MHz bandwidth.

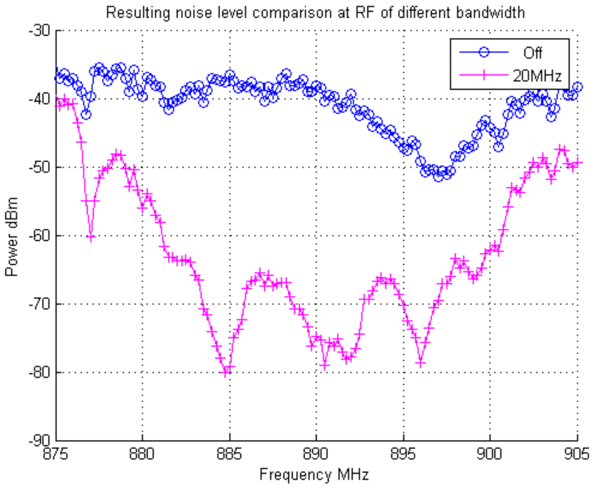

Fig. 4. Leakage level comparison with cancellation On/Off for 8 taps, centre frequency of 890MHz

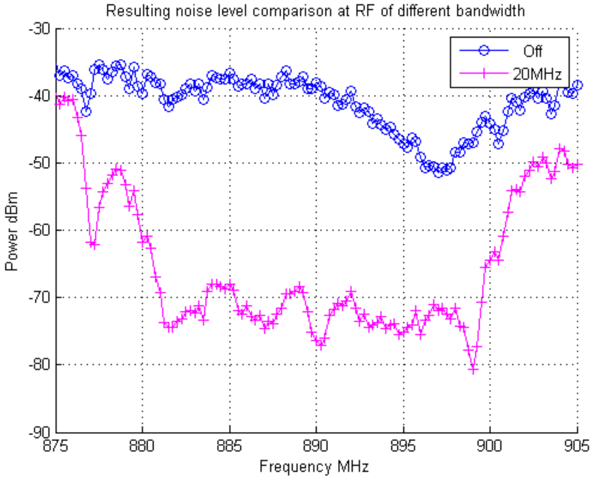

Fig. 5. Leakage level comparison with cancellation On/Off for 16 taps, centre frequency of 890MHz

V. CONCLUSION

An RF leakage cancellation structure with adaptive delay filter has been proposed in this paper. It briefly discusses the concept behind the proposed structure. It also provides simulation results of cancellation for 8 and 16 taps with 20 MHz bandwidth. Hardware implementations can be carried out for verification purpose in the future.

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