Modeling and Cancellation of Self-interference in Full-Duplex Radio Transceivers: Volterra Series–Based Approach

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***Abstract*—This paper presents a novel digital self-interference canceller for inband full-duplex radio transceivers. The proposed digital canceller utilizes a Volterra series with sparse memory to model the residual SI signal, and it can thereby accurately reconstruct the self-interference even under a heavily nonlinear transmitter power amplifier. To the best of our knowledge, this is the first time such a sparse-memory Volterra series has been used to model the self-interference within an inband full-duplex device. The performance of the Volterra-based canceller is evaluated with real-life measurements that incorporate also an active analog canceller. The results show that the novel digital canceller suppresses the SI by 34 dB in the digital domain, outperforming the state-of-the-art memory polynomial–based solution by a margin of 5 dB. The total amount of cancellation is nearly 110 dB with a transmit power of +30 dBm, even though a shared transmit/receive antenna is used. To the best of our knowledge, this is the highest reported cancellation performance for a shared-antenna full-duplex device with such a high transmit power level.**

***Index Terms*—Full-duplex, Self-interference, Digital cancellation, Volterra series, Nonlinear power amplifier**

I. INTRODUCTION

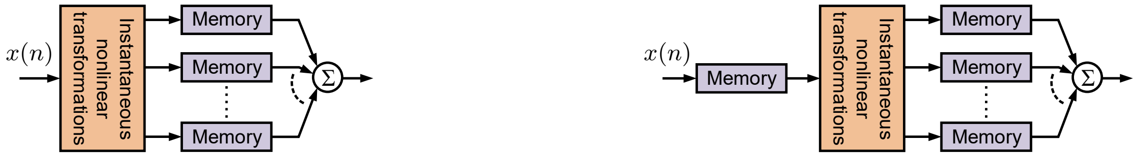
Inband full-duplex (IBFD) communications is a recent paradigm shift in the field of wireless communications that promises to as much as double the spectral efficiency of the existing systems [1], [2]. It achieves this by transmitting and receiving simultaneously on the same frequency channel within an individual device, as opposed to the current systems that always divide the transmission and reception either in time or in frequency. Such IBFD radio communication has long been thought to be impossible but recently several research groups have reported real-life demonstrator implementations that have achieved it in practice [2]–[7].

The main challenge in implementing an IBFD-capable radio transceiver is the so-called self-interference (SI), which is caused by the own transmitter (TX) chain operating simultaneously on the same frequency band as the receiver (RX) chain. Due to the close proximity of the TX and RX chains, the own transmit signal is extremely powerful upon reaching the receiver and therefore it will drown out everything else. In order to be capable of receiving a much weaker information signal, the SI must be suppressed, which can be done by regenerating the observed SI signal in the receiver using the known transmit data and subtracting it from the total RX signal. The regeneration must be done in accordance with the physical coupling channel as it determines how the transmit signal or SI will appear after propagating from the TX to the RX.

Although the general principle of SI cancellation is therefore rather simple, it is complicated by the analog impairments inherently present in any practical radio transceiver. The role of the impairments is particularly pronounced with very high transmit powers as then the required amount of SI cancellation is much larger. This calls for extremely accurate models to be used when regenerating such distorted SI within the canceller. So far, the highest transmit powers, with which the SI has been fully cancelled, have been in the order of +20...+25 dBm [4], [7]. One of the main limiting factors for the transmit power in IBFD devices is the nonlinearity of the transmitter power amplifier (PA), since the current SI cancellers cannot accurately model its nonlinear distortion beyond certain saturation levels.

To this end, this work proposes a novel technique for more accurately modeling and regenerating a nonlinearly distorted SI signal in the digital domain, based on a Volterra series with sparse memory. Volterra-based signal models have been widely used in other contexts, such as for digital predistortion (DPD) [8]–[11], but to the best of our knowledge this is the first time such a sparse-memory Volterra series is applied to digital SI cancellation in IBFD devices. Even though many earlier works have reported nonlinear digital cancellers [4], [6], [7], most of the existing solutions utilize a so-called memory polynomial (MP) signal model, which is not capable of modeling the SI signal accurately with very high-power amplifiers. The Volterra series–based model, on the other hand, remains accurate also under the more complex distortion waveforms produced by the high-power amplifiers, thereby providing the necessary amount of digital cancellation even with very large transmit powers.

The proposed novel digital canceller is evaluated in conjunction with our state-of-the-art shared-antenna IBFD prototype that incorporates also a real-time RF cancellation circuit. The obtained results indicate that the Volterra-based digital canceller can provide an improvement in the overall cancellation performance. Altogether, the prototype, together with the proposed digital canceller, can suppress the SI by nearly 110 dB, which is enough to facilitate IBFD operation with transmit powers in the order of +30 dBm.



(a)

(b)

Fig. 1: General illustrations of (a) a memory polynomial model and (b) a power amplifier model with memory both before and after the nonlinearity. Here, $x(n)$ denotes the baseband transmit signal.

II. SELF-INTERFERENCE IN FULL-DUPLEX DEVICES

The different SI cancellation or suppression mechanisms can be divided into roughly three categories: physical isolation, active analog cancellation, and active digital cancellation. The first simply involves maximizing the amount of physical isolation between the TX and RX chains. If using separate TX and RX antennas, this can be done, for instance, by increasing the distance between the antennas or placing them on the opposite sides of an absorbing element. In a shared-antenna IBFD device, the physical isolation can be maximized by connecting the TX and RX chains to the antenna via a circulator or an electrical balance duplexer (EBD). The former is a completely passive device, usually providing isolation in the order of 20–30 dB, while the latter is an active device that can isolate the TX and RX ports by over 40 dB [12].

After the physical isolation, further cancellation is usually needed to fully suppress the SI. To this end, most IBFD devices have two active SI cancellation stages, one of which operates in the RF domain while the other is done after the analog-to-digital conversion in the digital domain, as mentioned above. The RF canceller can use either the TX output signal or the digital baseband transmit data to generate the cancellation signal. The former option, which is the one utilized in the results reported in this work, has the benefit of suppressing also any potential impairments produced in the transmitter chain, although it has to resort to analog processing to regenerate the SI signal accurately. The latter option enjoys the increased flexibility of digital-domain processing but the upconverted RF cancellation signal does not automatically suppress the distortions possibly produced by the TX chain. Nevertheless, both of these methods have been reported to obtain 40–50 dB of RF cancellation [3], [13], [14].

In general, the role of the RF canceller is to ensure that the power of the remaining SI signal is sufficiently low for it to fit within the dynamic range of the RX chain, while the final cancellation stage is then typically done digitally [2]. The main challenge in digital cancellation is being able to model the overall effective coupling channel accurately. Namely, the digital canceller only has the original baseband transmit data at its disposal, while the observed SI signal contains the effects of various nonlinear impairments in the TX and RX chains. Previous works have shown that typically the strongest source of such distortion is the nonlinear PA, especially when considering a practical low-cost radio transceiver [2], [4], [15]. Therefore, accurate reconstruction of the SI typically requires the modeling of the PA-induced nonlinearities.

In almost all the existing works, the nonlinearity of the PA has been considered by modeling the SI signal with an MP signal model. In principle, it assumes the overall coupling channel to be as depicted in Fig. 1a, where each basis function produced by the nonlinearity has its own memory model. Such a modeling approach has been shown to perform well with reasonable transmit powers [6], [7]. However, an MP model implicitly assumes that all the memory effects occur *within and after* the nonlinear PA, which in reality might not be the case. Namely, the transmitter is usually frequency selective also before the nonlinear distortion occurs, meaning that the PA input signal has already experienced some memory effects [16]. This phenomenon is sufficiently weak not to be observable with the lower transmit powers used in the measurements so far, but it will contribute to the distortion waveform when the power level is increased.

To this end, in this work it is assumed that the SI signal is produced via the process depicted in Fig. 1b. That is, frequency selectivity both before and after the PA is taken into account, together with the nonlinearity of the PA itself, resulting in a model that remains accurate with much higher transmit power levels than the MP model. A widely adopted signal model for this type of a system is the Volterra series [8], which has so far been mostly used for digital predistortion. In this work, we utilize a sparse-memory version of the Volterra series for digital SI cancellation in IBFD devices, which, to the best of our knowledge, has not been done earlier.

III. MODELING THE SELF-INTERFERENCE WITH SPARSE VOLTERRA SERIES

As opposed to the regular Volterra series utilization reported, for instance, in [8], in this work the signal model has sparse memory taps, while also incorporating pre-cursor memory. These ensure that the digital canceller can model longer delay spreads and fractional delays, together with various other memory effects. Furthermore, in order to somewhat decrease the model complexity, lower memory depths are introduced for the higher nonlinearity orders. With these, the Volterra-based model for the SI in the digital domain can be written as

$$y_{\mathrm{SI}}[n] = \sum_{\substack{p=1\\ p\text{ odd}}}^{P} \sum_{m_1=-M_{1,p}}^{M_{2,p}} \sum_{m_2=m_1}^{M_{2,p}} \cdots \sum_{m_{(p+1)/2}=m_{(p-1)/2}}^{M_{2,p}} \sum_{m_{(p+3)/2}=-M_{1,p}}^{M_{2,p}} \cdots \sum_{m_p=m_{p-1}}^{M_{2,p}} \gamma_{p,m_1,\ldots,m_p}\phi_{p,m_1,\ldots,m_p}[n], \tag{1}$$

where P is the nonlinearity order, $M_{1,p}$ is the number of pre-cursor memory taps for the pth-order terms, $M_{2,p}$ is the number of post-cursor memory taps for the pth-order terms, $\gamma_{p,m_1,\ldots,m_p}$ is the coefficient of the corresponding term, and

$$\phi_{p,m_1,\ldots,m_p}[n] = \prod_{j=1}^{(p+1)/2} x[n-Lm_j] \prod_{k=(p+3)/2}^{p} x^*[n-Lm_k] \tag{2}$$

is the basis function of the Volterra series with sparse memory. Here, $x[n]$ represents the oversampled original digital transmit signal, and L is the decimation factor. The transmit data is oversampled due to the fact that the basis functions must be generated on a higher sampling rate to ensure that they will not alias on to the signal band [17]. For the same reason, the memory taps are spaced sparsely such that they are separated by unit sample intervals on the final cancellation sampling rate. As indicated by the measurement results, this ensures high cancellation performance by facilitating the modeling of longer delay spreads.

The total number of basis functions in the above Volterra-based model can be expressed as follows [8]:

$$n_{\mathrm{b}} = \sum_{\substack{p=1 \\ p \text{ odd}}}^{P} \binom{M_{1,p} + M_{2,p} + \frac{p-1}{2}}{\frac{p-1}{2}} \binom{M_{1,p} + M_{2,p} + \frac{p+1}{2}}{\frac{p+1}{2}} \tag{3}$$

After generating these basis functions on the higher sampling rate according to (2), they are decimated by a factor of L before being used for parameter learning and cancellation.

In principle, the unknown coefficients can be estimated using any suitable parameter learning tool. In this work, the parameter estimation is performed with the recursive squares (RLS) and block least squares (BLS) methods, the former obtaining the coefficient estimate iteratively while the latter uses a block of data to calculate the estimate. Both of these solutions do this by using a period of the observed SI signal $y_{\mathrm{RX}}[n]$, defined as

$$\mathbf{y}_{\mathrm{RX}} = \begin{bmatrix} y_{\mathrm{RX}}[0] & y_{\mathrm{RX}}[1] & \cdots & y_{\mathrm{RX}}[N-1] \end{bmatrix}^T, \tag{4}$$

where N is the size of the observation block and $(\cdot)^T$ denotes the transpose. Herein it is assumed that the observed SI signal $y_{\mathrm{RX}}[n]$ has already been decimated to the desired cancellation sampling rate.

It can then easily be determined based on (1) that the observed SI can be expressed as

$$y_{\mathrm{RX}}[n] = \boldsymbol{\gamma}^H \boldsymbol{\phi}[n] + z[n], \tag{5}$$

where $\boldsymbol{\gamma}$ is the unknown coefficient vector, $\boldsymbol{\phi}[n]$ is a vector containing all the decimated basis functions for a given time index n as given by (1)–(2), $z[n]$ represents the noise and modeling error, and $(\cdot)^H$ denotes the Hermitian transpose.

Considering first the RLS-based cancellation algorithm, the coefficient estimate vector is initialized as $\hat{\boldsymbol{\gamma}}_{\mathrm{RLS}}[0] = \mathbf{0}$, and the matrix $\mathbf{P}$ is initialized as $\mathbf{P}[0] = \delta\mathbf{I}$, where δ is a small quantity and $\mathbf{I}$ is the identity matrix. Then, the nth iteration of the algorithm is as follows:

$$\begin{aligned} y_{\mathrm{DC}}[n] &= y_{\mathrm{RX}}[n] - \hat{\boldsymbol{\gamma}}_{\mathrm{RLS}}[n-1]^H \boldsymbol{\phi}[n] \\ \mathbf{k}[n] &= \frac{\lambda^{-1}\mathbf{P}[n-1]\boldsymbol{\phi}[n]}{1 + \lambda^{-1}\boldsymbol{\phi}[n]^H \mathbf{P}[n-1]\boldsymbol{\phi}[n]} \\ \hat{\boldsymbol{\gamma}}_{\mathrm{RLS}}[n] &= \hat{\boldsymbol{\gamma}}_{\mathrm{RLS}}[n-1] + \mathbf{k}[n] y_{\mathrm{DC}}^*[n] \\ \mathbf{P}[n] &= \lambda^{-1}\mathbf{P}[n-1] - \lambda^{-1}\mathbf{k}[n]\boldsymbol{\phi}[n]^H \mathbf{P}[n-1] \end{aligned}$$

where λ is the forgetting factor and the iteration is performed over the N observed samples. Although the RLS-based approach allows for real-time tracking of the SI channel, it is also possible to cease the learning and use fixed coefficients for cancellation as long as the channel conditions remain static. The validity period of the coefficient estimates is determined by the SI channel coherence time, which highly depends on the environment [18].

Alternatively, in the case where temporal tracking is unnecessary, a fixed coefficient vector for the whole data block can be obtained with BLS as follows [2]:

$$\hat{\boldsymbol{\gamma}}_{\mathrm{BLS}} = \left[\left(\mathbf{X}^H\mathbf{X}\right)^{-1}\mathbf{X}^H\mathbf{y}_{\mathrm{RX}}\right]^* = \left(\mathbf{X}^T\mathbf{X}^*\right)^{-1}\mathbf{X}^T\mathbf{y}_{\mathrm{RX}}^*, \tag{6}$$

where the data matrix $\mathbf{X}$ is simply

$$\mathbf{X} = \begin{bmatrix} \boldsymbol{\phi}[0]^T \\ \boldsymbol{\phi}[1]^T \\ \vdots \\ \boldsymbol{\phi}[N-1]^T \end{bmatrix}, \tag{7}$$

and the complex conjugation is done to retain a uniform notation. The cancelled signal is then obtained as follows, similar to the RLS-based canceller:

$$y_{\mathrm{DC}}[n] = y_{\mathrm{RX}}[n] - \hat{\boldsymbol{\gamma}}_{\mathrm{BLS}}^H \boldsymbol{\phi}[n]. \tag{8}$$

In the forthcoming results, both of these estimation and cancellation solutions are utilized.

In general, the Volterra series is a rather complicated signal model as it is bound to contain a lot of basis functions, even with reasonably low nonlinearity order and memory depths, as is also evident from (3). Therefore, in order to utilize it in an actual implementation, a simpler parameter learning solution, together with some complexity reduction schemes, is most likely required. Nevertheless, in this work, the objective is to explore the boundaries of digital SI cancellation without considering the computational complexity. Replicating these results using signal models and estimators with more reasonable computational requirements is an important future work item for us.

IV. MEASUREMENT RESULTS

The proposed Volterra-based digital canceller is evaluated within a complete shared-antenna IBFD prototype depicted in Fig. 2. As discussed earlier, the prototype has also another active cancellation stage in the RF domain, which is a slightly improved version of the RF canceller reported in [13], although it still follows exactly the same architecture

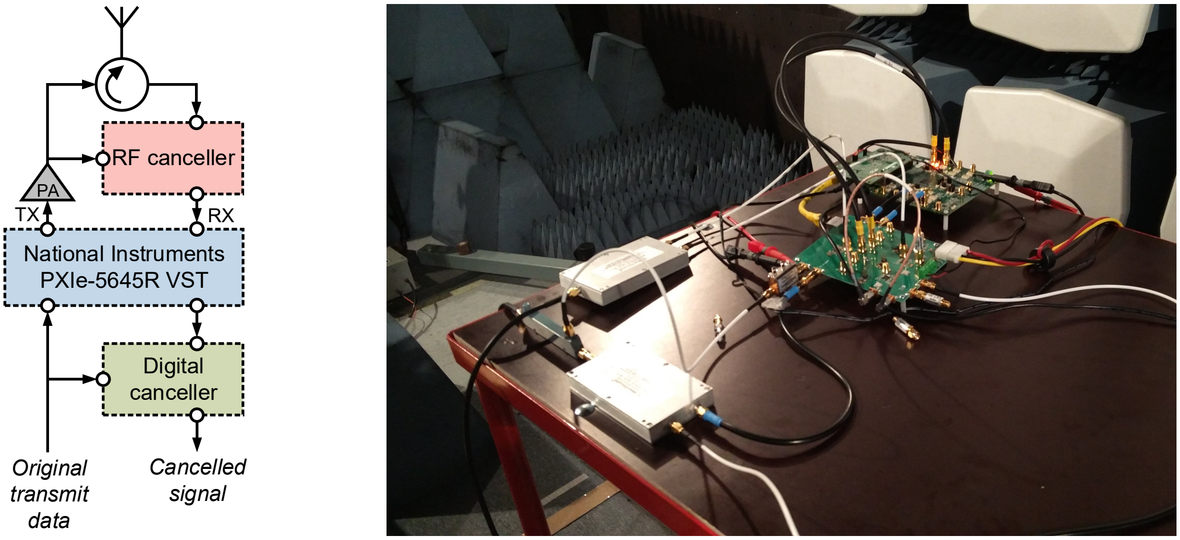


Fig. 2: Structural block diagram of the used measurement setup, together with a photograph taken in the actual measurement location.

and operating principle. The measurements are carried out on the unlicensed 2.4 GHz ISM band, using the parameters listed in Table I. The transmission and reception are done with the National Instruments PXIe-5645R vector signal transceiver (VST), the transmit signal being also amplified with a Mini-Circuits ZHL-16W-43-S+ PA. The PA output signal is then divided between the RF canceller and the circulator input since part of the TX signal must be used for RF cancellation. Upon reception, the circulator output signal, coming from the antenna, is first combined with the RF cancellation signal, which reduces the SI power. Due to the various couplers required in the RX path, the signal power is attenuated by roughly 7 dB before the RX input port of the VST, but this is taken into consideration in the reported overall cancellation performances.

The RF cancelled signal is then down-converted and digitized by the VST, after which the received digital samples are post-processed offline on a separate host computer, where the digital cancellation is performed with MATLAB. In this work, we compare the cancellation performance of three different digital cancellers: a linear digital canceller, an MP-based nonlinear digital canceller, and the proposed Volterra-based digital canceller. The linear canceller ignores all of the RF impairments, while the MP-based canceller models the nonlinearity of the PA using the MP model with the same nonlinearity order P as the Volterra-based canceller. Both of these reference solutions are described in detail in [2]. With the model parameters listed in Table I, the number of coefficients in the linear canceller is 51, while the nonlinear canceller has 255 coefficients. Moreover, using (3), the number of coefficients in the proposed Volterra-based model can be calculated as 2779, confirming the earlier deduction that it is indeed more complex than any of the existing models.

TABLE I: The essential measurement parameters.

Parameter		**Value**
Bandwidth		20 MHz
Transmit waveform		OFDM
Subcarrier spacing		15 kHz
PA gain		45 dB
Transmit power		+20...+33 dBm
Center frequency		2.48 GHz
RX losses		6.7 dB
RX sampling frequency		120 MHz
Decimation factor (L)		5
Number of samples used for estimation (N)		190 000
Linear canceller [2]	M_1	20
	M_2	30
MP-based nonlinear canceller [2]	M_1	20
	M_2	30
	P	9
Volterra-based nonlinear canceller	$M_{1,p}$	17, 4, 2, 1, 1
	$M_{2,p}$	20, 5, 3, 2, 1
	P	9

Since the vector modulators used within the RF canceller are rather noisy with the used power levels, the noise produced by the RF canceller is reduced in some of the forthcoming measurement results to more reliably evaluate the true digital SI cancellation performance, which is the main focus of this work. This is done by averaging the cancelled signal over many successive repetitions of the same transmit signal. Namely, as the residual SI is a function of the original transmit signal, it is not affected by the averaging, while the noise is reduced as it is obviously different from one repetition to the next. Moreover, in order to ensure that the residual SI is static between the consecutive repetitions, and to determine the ultimate steady-state performance of the

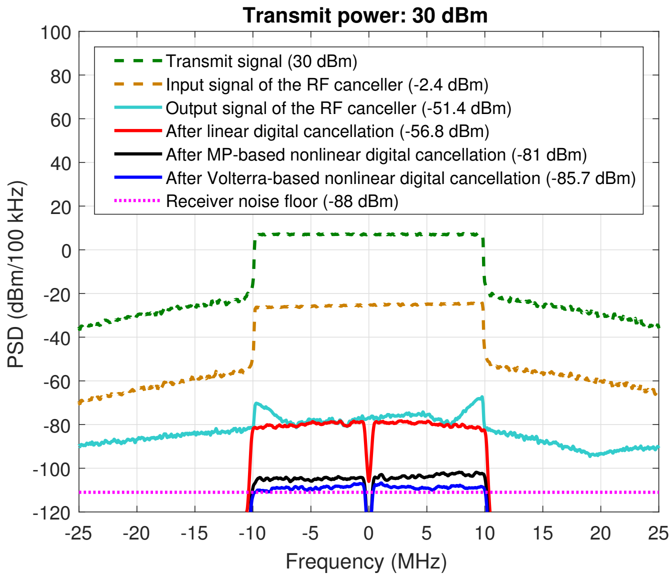


Fig. 3: Power spectral densities of the residual SI signal at different interfaces of the IBFD prototype.

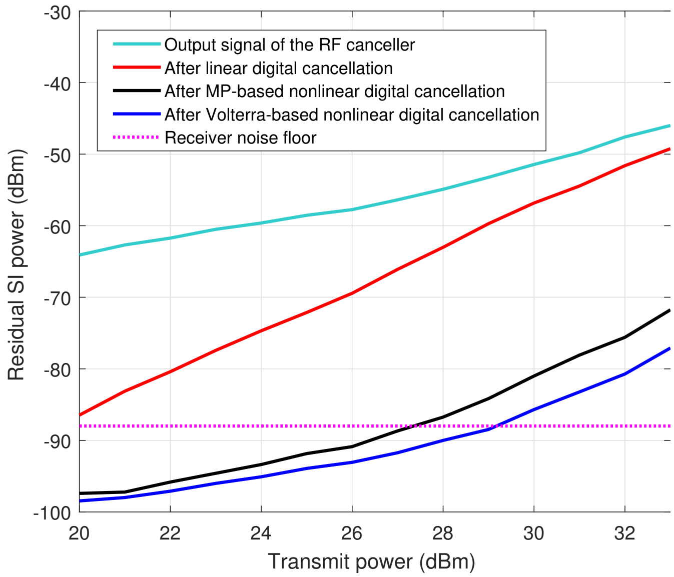


Fig. 4: Power of residual SI with respect to the transmit power.

RLS-based solution, the estimation and cancellation in the averaged results is performed with BLS, which estimates fixed SI channel coefficients for the whole block. This is facilitated by the fact that SI coupling channel can be expected to be identical between the different repetitions, as they occur within a very short time span. Thus, the residual SI is of the same form for all the repetitions, and consequently the averaging only removes the noise.

First, let us investigate the power spectral densities (PSDs) of the SI signal in various stages of the RX chain, using the default measurement parameters and a transmit power of +30 dBm. These are shown in Fig. 4, where the power levels have been referred to the RX input. Now, the amount of active RF cancellation is 49 dB, which is a slight improvement over the earlier version of the full-duplex prototype [6], [13]. As for the digital cancellation, it can be observed that resorting to the linear canceller or to the MP-based nonlinear canceller does not provide sufficient cancellation performance with the used transmit power of +30 dBm. In fact, with these digital cancellers, the residual SI is still 31 dB or 7 dB above the RX noise floor, respectively, significantly decreasing the reception performance. Compared to these existing solutions, the Volterra-based nonlinear canceller provides a clear improvement, canceling the SI within 2 dB of the RX noise floor. Considering the losses occurring in the RX path, the total amount of SI cancellation is therefore 109 dB with a +30-dBm transmit power, of which 34 dB is provided by the Volterra-based digital canceller. To the best of our knowledge, this is the highest reported cancellation performance for a shared-antenna IBFD radio transceiver under such a high transmit power.

Next, Fig. 4 shows the overall residual SI power with respect to the transmit power level. Again, the Volterra-based nonlinear canceller can be observed to consistently outperform the linear and MP-based nonlinear digital cancellers. Indeed, the linear canceller can suppress the SI satisfactorily only with the very lowest transmit powers, while the highest feasible transmit power for the MP-based nonlinear canceller is in the order of +25...+28 dBm. The Volterra-based canceller performs relatively well even with the transmit power of +33 dBm, although the residual SI is above the RX noise floor if the transmit power is more than +29 dBm. Altogether, these findings indicate that the memory effects captured by the Volterra series are significant with the higher transmit power levels, necessitating their modeling in the digital canceller of an IBFD radio transceiver.

Finally, to show that the RLS-based digital canceller can indeed achieve the same performance as obtained with the BLS, Fig. 5 shows the total residual powers for both cases when the RLS forgetting factor is $\lambda = 1$, calculated over a moving window of 1000 samples. Note that now the residual powers are not averaged as the residual SI is not exactly static due to the ongoing convergence and residual steady-state fluctuations of the RLS-based canceller. Nevertheless, it is evident that the RLS-based solution obtains the same total residual power level as the BLS, although it is not possible to evaluate its true residual SI power.

V. CONCLUSION

In this paper, we reported a novel digital canceller for inband full-duplex transceivers that relies on a sparse-memory Volterra series to model the residual self-interference. The Volterra series allows for more accurate modeling of the nonlinear distortion produced in the transmitter power amplifier, thereby facilitating higher transmit powers without resorting to expensive ultra-linear power amplifiers. The performance of the proposed digital canceller was evaluated with real-life RF measurements, where it was utilized within a shared-antenna full-duplex prototype incorporating also a state-of-

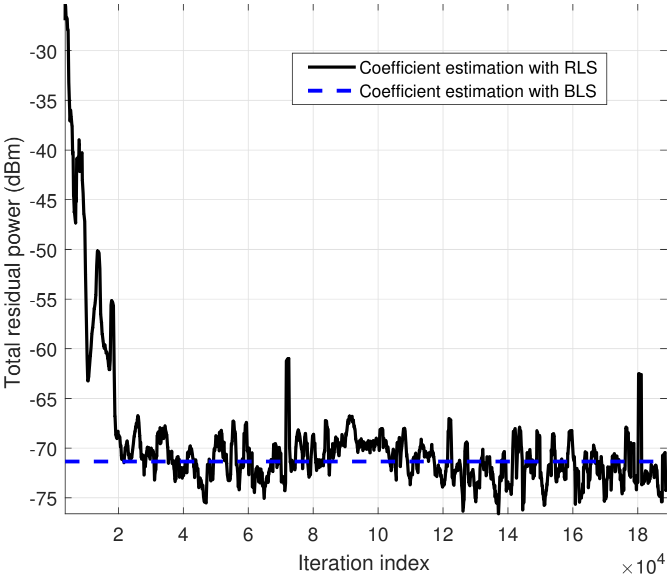


Fig. 5: Total residual power with respect to the iteration index of the RLS-based canceller without noise averaging.

the-art RF canceller. It was observed that the Volterra-based digital canceller outperforms the existing digital cancellation solutions, suppressing the SI by as much as 34 dB when using a transmit power of +30 dBm. With this, the total amount of self-interference suppression was nearly 110 dB, which is the highest reported cancellation performance for a shared-antenna full-duplex radio transceiver operating with such a high transmit power.

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