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Wavelet Decomposition based Channel Estimation and Digital Domain Self-Interference Cancellation in In-band Full-Duplex OFDM Systems

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Abstract

This paper presents a novel digital domain self-interference (SI) cancellation scheme for full-duplex (FD) OFDM systems employing noise robust SI channel estimation technique. First using the least-square (LS) technique, both the desired and the SI channels are estimated jointly assuming that the desired as well as SI signals are perfectly known. Since, LS estimator does not consider any noise effect in obtaining its solution, it may suffers from noise. Next, to suppress the noise effect, we propose wavelet decomposition (WD) of SI channel estimate to perform denoising in time domain. In the proposed algorithm, a standard deviation of noise obtained by WD is used as a threshold value which is a requisite to achieve an optimal performance. The simulation results show that the proposed algorithm outperforms the joint LS algorithm as well as the previous works using conventional LS where the desired signal is assumed as noise.

1 Introduction

Service proliferation with high data rate and capacity at any time, everywhere and to every body is the key objective of the upcoming wireless communication system which makes the efficient utilization of the limited spectrum a prerequisite. To achieve this, different techniques have been proposed in the past decades. Full- Duplex (FD) wireless communication system is emerging as the key enabling technology to achieve more flexible and improved spectrum utilization [1]. FD systems promote almost double spectrum efficiency to that of half duplex (HD) systems offering the potential for sustaining the evolution of the 5G technologies and this highly attracts the researchers to develop FD systems to enhance the overall capacity of the communication system [2]. The main hindrance of the FD system is the large self-interference (SI) created by the transmit antenna on the receive antenna within the same transceiver. Therefore, to make FD system feasible, a complete suppression of SI upto the receiver noise floor is required to achieve maximum capacity. In [3], the authors have reported that, first the SI cancellation is performed in the radio-frequency (RF) domain which reduces the total received power to an acceptable level that prevents the complete saturation of the receiver chain components. The remaining SI signal, called residual SI (RSI) is further suppressed in the digital domain [3].

In digital domain cancellation stage, the SI signal is subtracted from the received signal processed after analog-to-digital converter (ADC) at base band in the digital domain [4]. Digital domain cancellation techniques are highly attractive for FD systems as they are modulation independent which favors easy reconfiguration and use of highly efficient digital signal processing algorithms could further improve the system performance. In [4], the authors have modeled the SI signal in different transmit receive coupling stages in detail and proposed a novel digital SI cancellation technique which compensates the image component of the SI signal. In [5], the authors have utilized an auxiliary receiver chain that needs extra circuitry to obtain RF SI signal estimate in digital domain. A two stage iterative digital domain SI cancellation technique is proposed in [6] to enhance the accuracy where the preliminary estimate of the desired signal is used. In linear digital cancellation schemes, least squares (LS) is preferred due to its low complexity [7]. On the contrary, since LS estimator does not contemplate any noise effect in giving its solution, it is susceptible to noise.

In this paper, first the least complex LS estimation technique is used for the estimation of the SI channel considering the desired signal as noise. Next, both the desired and the SI channels are estimated jointly using the LS criterion in time domain. Further in order to compensate the vulnerability towards noise, we propose a wavelet denoising scheme on the SI channel estimate. WD is performed on estimate of SI channel obtained using joint LS technique to obtain threshold value which is a crucial facor on which noise reduction performance depends and this value must must be chosen appropriately to maximize the performance of the SI cancellation scheme. The proposed algorithm simulation study shows that the wavelet denoising gives better reduction in MSE of SI channel estimate as compared to conventional LS technique.

The rest of the paper is organised as follow: Section II presents a baseband system model of an Orthogonal frequency division multiplexing (OFDM) system operating in FD mode. In section III, novel SI channel estimation employing wavelet denoising over the SI channel estimate obtained using joint LS technique is presented. Section IV depicts the simulation results that validates the superiority of the proposed technique to that of the conventional LS estimation methods. Finally, conclusion is conveyed in section V.

2 System Model

We consider a OFDM based transceiver which is operating in FD mode by simultaneously transmitting and receiving the signal using the same frequency band. The simultaneous transmission and reception over the same frequency band results in SI which needs to be suppressed upto the receiver noise floor. This could be achieved by employing SI cancellation schemes at different stages of wireless communication system. In this work it is assumed that RF domain cancellation has already been performed and the desired signal to remaining SI power is 0 dB. The signal received at the FD radio receiver is expressed as:

$$y(n) = s(n) * h_{DS}(n) + x(n) * h_{SI}(n) + w(n). \quad (1)$$

Here, $h_{DS}(n)$ and $h_{SI}(n)$ are the discrete time Rayleigh fading channel coefficients of the desired signal $s(n)$ and the SI signal $x(n)$ respectively and $w(n)$ represents the AWGN noise. The discrete time channel impulse response of both the desired and SI signal is given by

$$h_i(n) = \sum_{l=0}^{L-1} \alpha_{il} \delta(n-l) \quad i = DS, SI \quad (2)$$

where α_{il} represents the attenuation associated with l_{th} path and l represents the different path delay index. L is the total number of delay paths.

3 Noise Robust Channel Estimation Based on WD

In this section, we perform digital domain SI cancellation to make practical FD system feasible. To achieve this we obtain a SI channel estimate which is used to reconstrunct the SI signal using known SI symbols. The reconstructed SI signal is further subtracted from the received signal after ADC in the digital domain. First using the conventional LS technique, SI channel is estimated where desired signal is considered as noise. Next, both the SI and the desired signal channels are estimated using the joint LS technique. Finally, we perform wavelet denoising on the SI channel estimate obtained using the aforementioned technique to reduce the noise vulnerability. The block diagram illustrating the proposed joint LS scheme followed by wavelet denoising is shown in Fig. 1.

3.1 Digital Domain SI Cancellation using Conventional LS Technique

In the conventional LS technique, the SI channel estimate is obtained considering the desired signal as noise and thus (1) reduces as:

$$y'(n) = x(n) * h_{SI}(n) + w'(n), \quad (3)$$

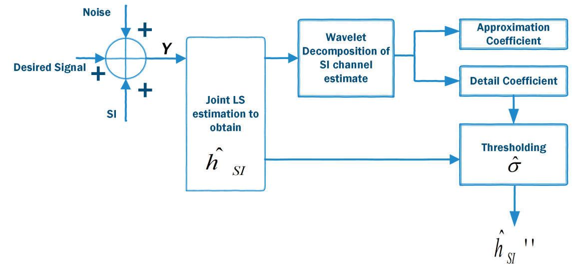

Figure 1. Block diagram of the proposed scheme using WD

where, $w'(n) = s(n) * h_{SI}(n) + w(n)$. The received signal vector for N observations is expressed as:

$$\mathbf{y}' = \mathbf{X}\mathbf{h}_{SI} + \mathbf{w}'(n). \quad (4)$$

Here, $\mathbf{X}$ represents the known SI symbol matrix and is given as:

$$\mathbf{X} = \begin{bmatrix} x(0) & \dots & x(N-1) & \dots & x(N-L) \\ \vdots & & \vdots & & \vdots \\ x(N-1) & \dots & x(N-2) & \dots & x(N-L-1) \end{bmatrix} \quad (5)$$

Applying LS criterion, the obtained SI channel estimate is represented as:

$$\hat{\mathbf{h}_{SI}}' = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{y}'. \quad (6)$$

The estimated SI signal using the known SI symbols is reconstructed as:

$$\hat{\mathbf{x}} = \mathbf{X}\hat{\mathbf{h}_{SI}}'. \quad (7)$$

For SI cancellation, the reconstructed SI signal is subtracted from the total baseband received signal which is expressed as:

$$\hat{\mathbf{y}}' = \mathbf{y}' - \hat{\mathbf{x}}. \quad (8)$$

3.2 WD based Digital Domain SI Cancellation in In-band FD Systems

In this work, we propose wavelet denoising operation on the obtained SI channel estimate utilizing the joint LS technique in [9]. Here, it is assumed that, the desired signal is perfectly known to the receiver and both the desired and SI channels are estimated jointly as follows:

$$\begin{bmatrix} \hat{\mathbf{h}_{DS}} \\ \hat{\mathbf{h}_{SI}} \end{bmatrix} = [\mathbf{S}\ \mathbf{X}]^{\#}\mathbf{y}. \quad (9)$$

Here, # represents the conjugate transpose operation and $\mathbf{S}$ is the desired signal matrix represented as:

$$\mathbf{S} = \begin{bmatrix} s(0) & \dots & s(N-1) & \dots & s(N-L) \\ \vdots & & \vdots & & \vdots \\ s(N-1) & \dots & s(N-2) & \dots & s(N-L-1) \end{bmatrix}, \quad (10)$$

where, N is the total number of observations. The signal received after SI cancellation is expressed as:

$$\hat{\mathbf{y}} = \mathbf{y} - \hat{\mathbf{x}}, \quad (11)$$

where, $\hat{\mathbf{x}} = \mathbf{X}\hat{\mathbf{h}_{SI}}$ represents the estimated SI signal using joint LS technique. The channel estimation is the basic requirement for coherent detection in OFDM systems but the LS algorithm does not care about noise in obtaining its solution, so, it is subjected to noise. To overcome this, wavelet denoising is performed over the LS estimate of the SI channel. In WD scheme, signals are divided into approximation and detail coefficients. Smoothing filter like moving averaging filters are used to obtain approximation coefficients and similarly detail coefficients are obtained using high pass filters. The smoothing filter impulse response $h'(n)$ and high pass filter impulse response $g'(n)$ used for the Haar wavelet are represented as:

$$h'(n) = \frac{1}{2}\delta[n] + \delta[n+1]$$

$$g'(n) = \frac{1}{2}\delta[n]\delta[n+1], \tag{12}$$

where, δ is the Kronecker delta function and is expressed as:

$$\delta[n] = \begin{cases} 1, & n = 0 \\ 0, & n \neq 0. \end{cases} \tag{13}$$

The standard deviation of the detail coefficients corresponding to noise added to the signal can be obtained by [8] as:

$$\hat{\sigma} = \frac{median|D_i|}{0.6745}, \tag{14}$$

where, D_i represents the detail coefficients obtained employing wavelet decomposition on the SI channel coefficient estimate obtained using joint LS estimation technique and the obtained $\hat{\sigma}$ is used as a threshold value to reduce the unavoidable noise effects on the SI channel estimate. Thus, the threshold value, $\hat{\sigma}$ obtained in (14) can also be used as a theoretical value for reducing the noise effect in SI channel estimation in time domain. Applying threshold operation, noise suppressed SI channel coefficients are obtained as:

$$\hat{\mathbf{h}_{SI}}'' = \begin{cases} \hat{\mathbf{h}_{SI}}, & \hat{\mathbf{h}_{SI}} \geq \hat{\sigma}, \\ 0, & \hat{\mathbf{h}_{SI}} < 0 \end{cases} \tag{15}$$

By following the above principle, the insignificant SI channel coefficients which are smaller than the threshold value are suppressed.

4 Simulation Performance

This section is devoted to the performance evaluation of the proposed digital domain SI cancellation scheme using Matlab simulation. In the presented work, we consider a system comprising of two OFDM based transceivers and each of them are operating in FD mode i.e. simultaneously transmitting and receiving over the same frequency band. The simulation parameters are listed as: System bandwidth considered is 20 MHz. The FFT size is 64 and CP length is 16. Out of 64, 52 subcarriers are occupied. The pilot spacing taken is 4. The conventional modulation scheme used for transmit symbols on each subcarrier are BPSK and 16 QAM. For ease of simulation, no coding and data scrambling are used. The far end and the near end channels ie. desired and SI channels are modeled as multipath Rayleigh fading with 3 channel taps each. We assume that, there were no frequency offset and synchronization error. To obtain the threshold value, we used D_i which is one of the well known filters for a wavelet decomposition to estimate the channel values varying with time [8]. In this section, we have obtained the mean square error (MSE) and bit error rate (BER) to compare the performance of the proposed methods based on noise reduction in SI channel estimate by

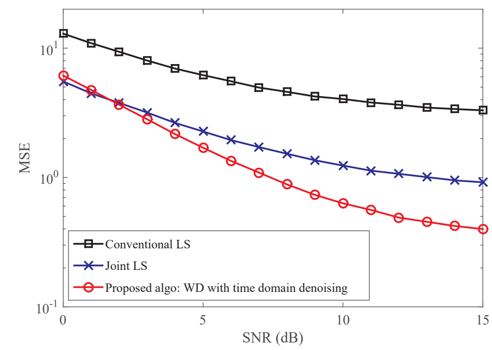

Figure 2. MSE Vs SNR (dB) using different SI channel estimation techniques in BPSK OFDM system.

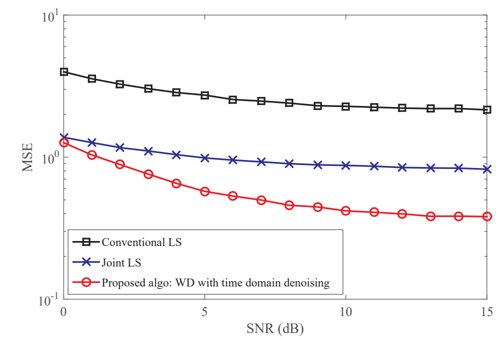

Figure 3. MSE Vs SNR (dB) using different SI channel estimation techniques in 16 QAM OFDM system.

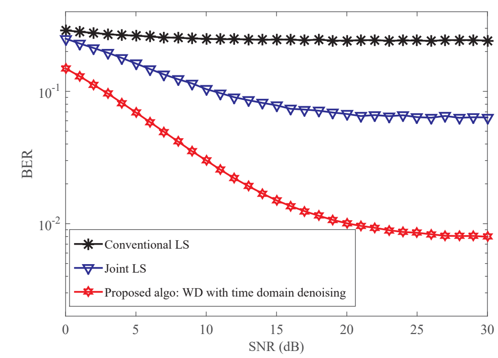

Figure 4. BER Vs SNR (dB) for BPSK OFDM system after SI cancellation.

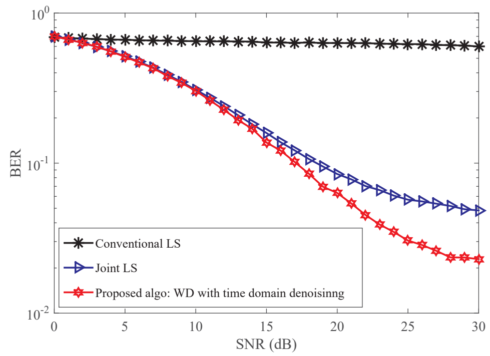

Figure 5. BER Vs SNR (dB) for 16 QAM OFDM system after SI cancellation.

WD to that of conventional LS scheme.

Fig. 2. and Fig. 3. depict the MSE of the proposed algorithm used for estimating SI channel in BPSK OFDM and 16 QAM OFDM respectively. For evaluating the performance of the proposed algorithm, MSE of the algorithm is compared with the MSE using LS technique at different values of signal-to-noise-ratio (SNR). From both the figures, it is clearly inferred that MSE of the proposed SI channel estimation employing wavelet decomposition outperforms conventional LS approach assuming the desired signal as noise and the joint LS algorithm as well. Wavelet denoising reduces the noise effect on the SI channel estimate and thus provides better performance.

BER curves after one tap equalization followed by decoding with BPSK OFDM is shown in Fig. 4. It is clearly shown in Fig. 4., that the proposed scheme raises the SI channel estimation performance and thus reduces BER in comparison to the conventional LS method. An optimal BER performance is obtained at high SNR values because at low SNR, the thermal noise is dominant as compared to the unknown transmitted signal and the estimation performance is mostly effected by the thermal noise [9]. Fig. 5. represents the BER curves of the proposed schemes and the conventional LS method for 16-QAM OFDM system. All the legends are similar to that of Fig. 4. It clearly depicts that the proposed algorithm improves the joint LS technique and greatly outperforms the conventional LS approach where, the desired signal is assumed as noise.

5 Conclusion

In this paper, noise robust SI channel estimation technique for digital SI cancellation in FD OFDM system is proposed. Since, LS estimator does not contain any noise effect in obtaining its solution, it may become vulnerable to noise. To overcome this, we propose wavelet denoising over the SI channel estimate obtained using the joint LS technique in time domain. The performance of the proposed denoising scheme depends on the selection of an appropriate threshold value. The simulation results show that the proposed algorithm gives better performance in terms of MSE and BER as compared to the conventional LS approach. The SI channel estimation noise could be effectively suppressed by adopting the proposed algorithm and thus noise robust SI channel coefficients for baseband SI cancellation irrespective of channel conditions and bit rates could be obtained.

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