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# Self-interference Cancellation in In-band Full-duplex Communication Systems Using Special Pair of Complementary Sequences

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## Abstract

This paper presents a digital domain self-interference (SI) cancellation algorithm employing complementary sequence pair based LS technique for in-band full-duplex (FD) orthogonal-frequency-division multiplexing systems over Rayleigh frequency selective fading scenario. Here SI channel estimation is performed under two scenarios. To obtain an efficient and reliable SI channel estimate, the intended signal transmitter is kept off in the first scenario, whereas the intended signal is considered as noise in the second scenario. For the estimation of the SI channel coefficients, special pairs of complementary sequences are constructed that reduces the complexity of time domain channel estimation. Further, SI cancellation is performed in digital domain to make practical FD system feasible. The simulation performances of the proposed algorithm outperforms the conventional techniques that proves its feasibility.

## 1 Introduction

In-band full-duplex (FD) communication system that allows simultaneous transmission and reception over the same frequency band is emerging as the key enabling technology for the upcoming generation of wireless communication system. Simultaneous transmission and reception over the same frequency band in in-band FD system aims to almost double the spectrum efficiency as compared to half-duplex system [1]. 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 that needs to be properly canceled out from the received signal so that, the intended signal i.e signal of interest could be detected successfully. First SI cancellation is performed in propagation domain followed by radio-frequency domain [2]. The remaining SI signal called residual SI (RSI) is further suppressed in the digital domain where, the SI signal is subtracted from the received signal processed after analog to digital converter at baseband in the digital domain and this stage is referred as digital domain cancellation stage [3].

To perform SI cancellation in digital domain, the SI signal could be estimated accurately and efficiently from the transmitted symbols known to the receiver. Practically, channel estimation errors hinder the performance of the possibility of canceling SI completely. Hence, accurate and reliable SI channel estimation is becoming the key challenge in FD systems. Frequency domain least square (LS) estimation was presented in [4]. In [5], the authors proposed another approach to implement the LS technique by iterating between the intended signal detection and the channel estimation. However, in the aforementioned SI channel estimation techniques, the intended signal i.e. signal from the desired transmitting antenna is treated as noise which reduces the performance. In [6], the authors have considered LS estimation for FD relay. An adaptive least mean square technique was proposed in [7], where, SI is assumed very large in comparison to desired signal and noise. The drawback of this scheme was that it needed many iterations to converge.

In OFDM systems with burst transmission, usually time-multiplexed preamble is employed for channel estimation. As far as accuracy is concerned, time domain channel estimation outperforms frequency domain estimation technique since, in time domain estimation, number of channel impulse responses to be estimated is reduced [8]. However, in OFDM systems, as the number of channel taps increase, complexity of time domain based channel estimation using general training sequences also increases [8]. The above issue is considered in this paper and a special pair of complementary sequences is used that reduces the complexity of time domain channel estimation by virtue of its autocorrelation property.

In this paper, the performance of the proposed digital domain SI cancellation algorithm is investigated under two scenarios. The investigation is carried out considering the frequency selective fading channel. The major contributions in this paper are summarized as follows:

- Unlike some previously reported work where complementary sequence pairs has been used for channel estimation in half duplex QPSK system [9], in this paper complementary sequence pairs based LS technique for SI channel estimation in FD OFDM system is performed which has not been reported so far as per author's knowledge.
- The analysis is carried out under two different scenarios. In the first scenario, the SI channel estimation is performed in FD-OFDM system considering intended signal transmitter off and in the second scenario, the intended signal is considered as random noise.
- Next, SI cancellation is performed in digital domain by subtracting an SI signal estimate from the total received signal at FD radio receiver.

- The simulation performance of the proposed algorithm is compared with the conventional LS techniques. Finally, the comparison results depict that the proposed algorithm employing complementary sequence pair based LS technique outperforms the conventional LS technique that affirms its utility.

The remaining sections of this paper are organized as follows: Section 2 describes the system model of the proposed work. SI channel estimation using conventional LS method and complementary sequence pair based LS technique is presented in section 3. In section 4, the results of the simulation performances of compared SI cancellation approaches is depicted and finally section 5 concludes the paper.

## 2 System model

In this work, we have considered a OFDM based two transceiver that operates in FD mode i.e. it is transmitting and receiving simultaneously using the same frequency band. The signal received at $n^{th}$ instant of FD radio receiver is expressed as:

$$y(n) = x(n) * h_x(n) + s(n) * h_s(n) + w(n), \quad n = 0, 1, ...N-1 \tag{1}$$

where, $x(n)$ and $s(n)$ are the intended signal and SI signal respectively, $w(n)$ is the AWGN noise and $N$ represents the total number of observations. The discrete time channel impulse response of both the SI signal and intended signal is expressed as:

$$h_i(n) = \sum_{0}^{L-1} \beta_{il} \delta(n-l), \;\; i = s, x \tag{2}$$

where, $\beta_{il}$ is the attenuation of the $l^{th}$ path of the signal and $l$ denotes index of the different path delay. $L$ represents the total number of delay paths.

Here, for SI channel estimation, complementary sequence pairs are preferred as it reduces the time domain channel estimation complexity. A pair of sequences $\mathbf{a} = [a(0), a(1), .....a(N-1)]^T$ and $\mathbf{b} = [b(0), b(1), .....b(N-1)]^T$ where, $N$ is the length of the sequence is called a pair of complementary sequence if their aperiodic autocorrelation function $R(\tau)$ satisfy the following property[10]:

$$R(\tau) = R_a(\tau) + R_b(\tau) = 0 \quad if \; \tau \neq 0$$

$$R(\tau) = R_a(\tau) + R_b(\tau) = 2N \quad if \; \tau = 0. \tag{3}$$

Here, $R_a(\tau)$ and $R_b(\tau)$ are the aperiodic autocorrelation of $a$ and $b$ respectively which are expressed as:

$$R_a(\tau) = \sum_{k=0}^{N-1-\tau} a(k)a(k+\tau) \; and \; R_b(\tau) = \sum_{k=0}^{N-1-\tau} b(k)b(k+\tau). \tag{4}$$

Complementary sequences could be constructed by applying various methods. In this paper, one of the method presented in [10] has been utilized to construct the complementary pair sequences so that SI channel estimation could be implemented in time domain with reduced complexity. Let, initially the sequence **a** and **b** at $0^{th}$ step is given as: $a_0 = 1$ and $b_0 = 1$ respectively and the length of sequence, $N$ is given as: $n = 2^P$ where, $P = 0, 1, 2$. Considering the afore stated assumptions using recursive method, the complementary sequence pairs at $p^{th}$ step could be constructed as:

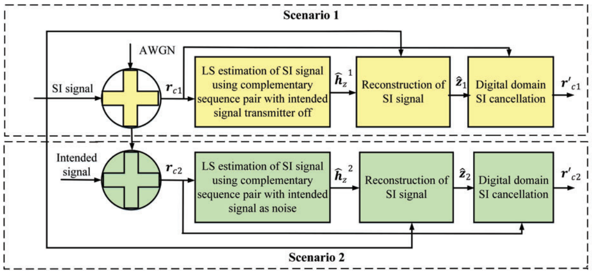

**Figure 1.** Block diagram of the proposed digital domain SI cancellation algorithm

$$\mathbf{a}_p = [a_p(0,), a_p(1), .....a_p(2^P-1)]^T \quad p = 1, 2, ...P \; and$$

$$\mathbf{b}_p = [b_p(0,), b_p(1), .....b_p(2^P-1)]^T \quad p = 1, 2, ...P. \tag{5}$$

## 3 LS based digital domain RSI cancellation using complementary sequence pairs

In this section, LS based RSI cancellation is presented in digital domain using complementary sequence pairs. First, conventional pilot based LS estimation is performed to obtain SI channel estimate. Further, using complementary sequence pairs, LS technique is employed to estimate the SI channel. The analyis is carried out under two scenarios where, in the first scenario, the intended signal transmitter is kept off and intended signal is considered as noise in the second scenario. The block diagram of the proposed algorithm is presented in Fig. 1.

### 3.1 Pilot based LS estimation of SI channel

The $n^{th}$ sample of the signal received at FD radio receiver under first scenario considering intended signal transmitter off is expressed as:

$$r_1(n) = \sum_{0}^{L-1} s(n-L) h_s^1(l) + w(n), \tag{6}$$

where, $n = 0, 1, ...N-1$, w(n) denotes the white Gaussian noise, $L$ is the total number of paths, $s(n)$ is the SI signal and $h_s$ is the SI channel coefficient. In linear model, the above equation could be expressed as:

$$\mathbf{r}_1 = \mathbf{S}\mathbf{h}_s^1 + \mathbf{w}_1, \tag{7}$$

where, $\mathbf{h}_s^1 = [h_{s_0}^1 \; h_{s_1}^1 \; ..h_{s_{L-1}}^1]$ is the SI channel impulse response vector, $\mathbf{w}_1$ is the noise vector. $\mathbf{S}$ is a circular matrix with order $N \times L$. Since the signal transmitted by the SI transmitter is known to the transceiver, the matrix $\mathbf{S}$ could be precomputed and thus the SI channel estimate could be expressed as:

$$\hat{\mathbf{h}_s^1} = \mathbf{S}^{\dagger}\mathbf{r}_1, \tag{8}$$

where, † represents the psuedo inverse operation. Under the second scenario where intended signal is considered as noise, the received $n^{th}$ sample at FD radio is expressed as:

$$r_2(n) = \sum_{0}^{L-1} x(n-L)h_x(l) + \sum_{0}^{L-1} s(n-L)h_s^2(l) + w_2(n), \quad (9)$$

where, $x(n)$ is the signal from intended transmitter and $w_2(n)$ is the noise. Considering the intended signal as noise, the above equation could be expressed as:

$$r_2'(n) = \sum_{0}^{L-1} s(n-L)h_s^2(l) + w_2'(n), \quad (10)$$

where, $w_2'(n)$ is the coloured noise. Further, the linear model formulation of the received signal could be expressed as:

$$\mathbf{r}_2 = \mathbf{S}\mathbf{h}_s^2 + \mathbf{w}_2', \quad (11)$$

where, $\mathbf{h}_s^2 = [h_{s_0}^2 \ h_{s_1}^2 \ ..h_{s_{L-1}}^2]$ is the SI channel vector and $\mathbf{w}_2'$ is the noise vector for second scenario. Similar to (8), the SI channel estimate under second scenario is obtained as:

$$\hat{\mathbf{h}_s^2} = \mathbf{S}^{\dagger}\mathbf{r}_2. \quad (12)$$

### 3.2 Proposed SI channel estimation using complementary sequence pair based LS criterion

First, a time multiplexed preamble for SI signal is designed as follow:

$$\begin{aligned} \mathbf{z} &= [z(0) + z(1) + .....z(M-1)]^T \\ &= [\mathbf{0}^T \ \mathbf{a}^T, \mathbf{0}^T, \mathbf{0}^T, \mathbf{b}^T, \mathbf{0}^T]^T, \end{aligned} \quad (13)$$

where, $\mathbf{0}$ is a $K \times 1$ vector with zero elements and $M = 2N+4$. **K** is the length of the preamble and the transpose operator is denoted by $[\ ]^T$. Under first scenario with intended transmitter off, the received discrete time signal is represented as:

$$r_{c1} = \sum_{l=0}^{L-1} z(n-l)h_z^1(l) + w_{c1}(n). \quad (14)$$

In vector form, the received signal vector and the SI signal vector is given as: $r_{c1} = [r_{c1}(0), r_{c1}(1) ......r_{c1}(M+L-2)]^2$ and $\mathbf{z} = [0...0 \ \ z^T \ ,0...0]^T$ respectively. Further, the received signal in linear model could be expressed as:

$$\mathbf{r}_{c1} = \mathbf{Z}\mathbf{h}_z^1 + \mathbf{w}_{c1}, \quad (15)$$

where, $\mathbf{Z}$ is the $(M+L-2) \times L$ circular matrix and $\mathbf{h}_z^1$ is the $L \times 1$ SI channel vector under scenario 1. Now, using LS technique employing complementary sequence pairs property, the SI channel estimate in time domain could be computed as as:

$$\hat{\mathbf{h}_z^1} = (\mathbf{Z}^T\mathbf{Z})^{-1}\mathbf{Z}^T\mathbf{r}_{c1} = \frac{1}{2N}\mathbf{Z}^T\mathbf{r}_{c1}, \quad (16)$$

where, $(\mathbf{Z}^T\mathbf{Z}) = 2N$. Similarly, under second scenario with intended signal as noise, the received signal at FD radio receiver is expressed as:

$$r_{c2} = \sum_{l=0}^{L-1} z(n-l)h_z^2(l) + w_{c2}'(n), \quad (17)$$

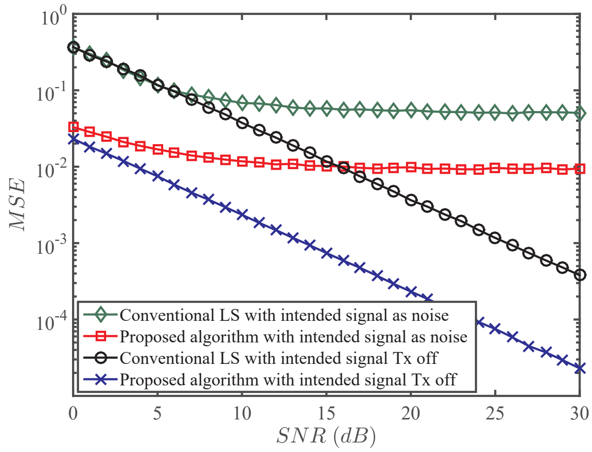

**Figure 2.** MSE vs SNR

where, $w_{c2}'(n)$ is the coloured noise comprising of intended signal and AWGN noise which could be expressed as:

$$w_{c2}'(n) = \sum_{0}^{L-1} x(n-l)h_x(l) + w_{c2}(n). \quad (18)$$

Again in linear model, the received signal could be expressed as:

$$\mathbf{r}_{c2} = \mathbf{Z}\mathbf{h}_z^2 + \mathbf{w}_{c2}. \quad (19)$$

Here, $\mathbf{h}_z^2$ is the $L \times 1$ SI channel vector under scenario 2. Next, SI channel estimate using LS criterion under second scenario considering intended signal as noise could be obtained as:

$$\hat{\mathbf{h}_z^2} = (\mathbf{Z}^T\mathbf{Z})^{-1}\mathbf{Z}^T\mathbf{r}_{c2} = \frac{1}{2N}\mathbf{Z}^T\mathbf{r}_{c2}, \quad (20)$$

where, $(\mathbf{Z}^T\mathbf{Z}) = 2N$ using the property of complementary sequence pairs. Further, the SI signal under the two aforementioned scenarios could be reconstructed and finally, SI cancellation in digital domain could be performed by subtracting the estimated SI signal from the total received signal which could be expressed as:

$$\mathbf{r}_{ci}' = \mathbf{r}_{ci} - \hat{\mathbf{z}}_i, \quad (21)$$

where, i=1,2 represents the first and second scenario respectively and $\hat{\mathbf{z}}_i = \mathbf{Z}\hat{\mathbf{h}_z^i}$.

## 4 Performance Analysis

In this section, we evaluate and compare the performance of the proposed cancellation schemes in terms of the mean square error (MSE), bit error rate performance (BER) and the desired signal-to-SI-plus-noise power ratio (SINR) after SI cancellation. We have considered FD system using OFDM-BPSK with N = 64 subcarriers. The wireless channels are represented by a multipath Rayleigh fading model with L = 3 paths. Fig. 2 represents the MSE vs SNR (dB) performance comparison of the proposed LS based algorithm using complementary sequence pairs to that of conventional pilot based LS technique for SI cancellation under two scenarios considering intended signal transmitter

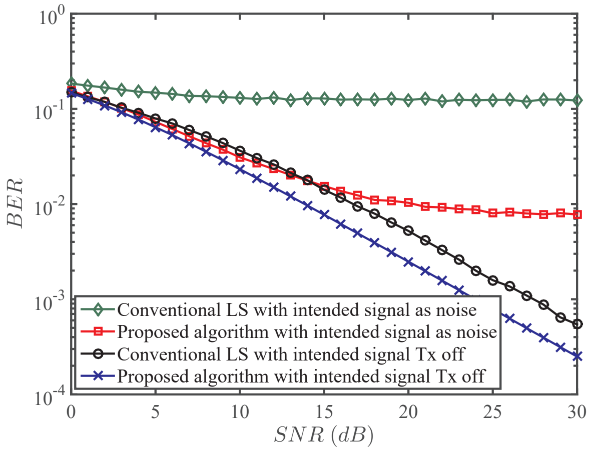

**Figure 3.** BER vs SNR

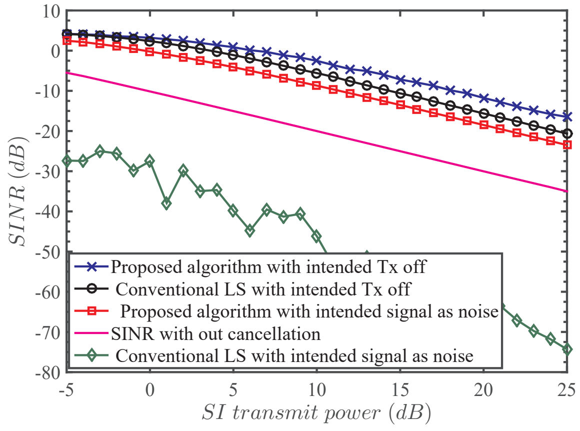

**Figure 4.** SINR vs SI transmit power

off and intended signal as random noise. The proposed algorithm under scenario 1 where intended transmitter is kept off, outperforms the rest discussed techniques as use of special pair of complementary sequences helps in gaining more accurate SI channel estimate and it reduces the complexity of time domain channel estimation as well. The same helps in obtaining a reduction from $10^{-2}$ to $10^{-0.6}$ in MSE even at a low SNR value of 5 dB.

Fig. 3 depicts BER vs SNR(dB) plot after SI cancellation to compare the performances of the proposed algorithm with the conventional techniques. BER performance improves with the increase in the value of SNR as at high SNR, the influence of noise decreases. The proposed algorithm under scenario 1 upgrades the estimation performance and outperforms the conventional techniques. A significant SNR gain of 4 dB is achieved at a BER of $10^{-3}$ using the proposed algorithm under scenario 1 compared to the conventional LS technique.

Fig. 4 shows the impact of high RSI power on different discussed digital domain SI cancellation schemes. At constant noise power of 5 dB, as SI transmit power increases SINR decreases and a RSI cancellation of 18 dB is achieved with the proposed algorithm under scenario 1 when SI transmit power is 25 dB. This figure also depicts that under second scenario considering intended signal as noise, the performance of the conventional LS technique is worse as the impact of random noise becomes more prominant. Further, at high SNR, the proposed algorithm employing complementary sequence pair based LS technique under the scenario considering intended signal transmitter off outperforms the conventional techniques in terms of output SINR.

## 5 Conclusion

In this paper, an efficient and reliable digital domain SI cancellation algorithm is proposed for in- band FD OFDM system over Rayleigh frequency selective fading channel. In the proposed algorithm, SI channel is estimated using least square technique employing special pair of complementary sequences. The results demonstrated that the proposed algorithm reduces the channel estimation error and consecutively BER also get reduced. Under the first scenario with intended signal transmitter off, using the proposed algorithm at SNR 25 dB, the MSE reduces from $10^{-4}$ to $10^{-3}$ and BER also reduces to $10^{-3}$. An achievement of 4 dB SNR gain at BER of $10^{-3}$ is obtained using the proposed algorithm with intended signal transmitter off. The result also depicts that SINR could be enhanced from -35 dB to -17 dB using the proposed algorithm under scenario 1 at SI transmit power 25 dB that validates its applicability for future wireless applications.

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