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A New In-band Full-duplex SIC Scheme Using a Phase Rotator

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** Short Paper*

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***Abstract*:** How well the self-interference cancellation (SIC) technique performs is a primary issue in realizing an in-band full-duplex (FD) wireless communication system. One factor affecting its performance is channel estimation error on the self-interference channel. We propose a new analog SIC scheme which is robust to channel estimation error. It uses phase rotators in the radio frequency (RF) chain. We also derive closed-form equations for the residual self-interference of the proposed and the conventional schemes. The analytical and numerical results show that the residual self-interference under the proposed SIC scheme is less than that using the conventional scheme, even though channel estimation error is present.

***Keywords*:** Full-duplex, Self-interference cancellation, Channel estimation error

1. Introduction

In-band full-duplex (FD) systems, which simultaneously transmit and receive data on the same frequency band, have recently arisen as a promising technique to improve spectral efficiency for future wireless communication systems. Compared with conventional half-duplex (HD) systems, FD systems ideally achieve twice the spectral efficiency [1, 2].

However, when FD nodes simultaneously exchange their data, it causes strong self-interference [3]. This is because the desired signal from the pair node is more greatly attenuated than the self-interference signal from its own transmitter. This strong self-interference degrades the signal-to-interference-plus-noise ratio (SINR) and throughput performance.

A variety of self-interference cancellation (SIC) schemes have been proposed to improve FD system feasibility [3-7]. These SIC techniques can be divided into three categories: passive, analog, and digital. Passive SIC reduces the self-interference before it enters the analog circuit. Analog SIC is then used for suppressing self-interference on the analog circuit before the analog-to-digital converter (ADC). Lastly, digital SIC cancels the self-interference after the ADC.

Analog SIC schemes estimate the self-interference and subtract it from the received signal. There are two types of analog SIC implementation [3]. In the first, the attenuation and delay of the transmitted analog signal are revised to match the self-interference and to subtract from the received signal [8]. The second type is done by applying the attenuation and delay in the digital domain and converting it to the analog domain so it can then be subtracted from the received signal [4].

Because analog SIC operates based on the estimated channel information, the performance of analog SIC is directly sensitive to the channel estimation accuracy. In practical wireless communication systems, however, channel estimation error occurs over a limited dynamic range and through noise at the receiver. The result is that the channel estimation error degrades the performance of the analog SIC techniques [4].

In this letter, we propose a new analog SIC scheme which is robust to channel estimation error. The proposed analog SIC uses phase rotators to align the self-interference with the orthogonal direction of the desired signal and to suppress the self-interference. This is different from the two conventional analog SIC

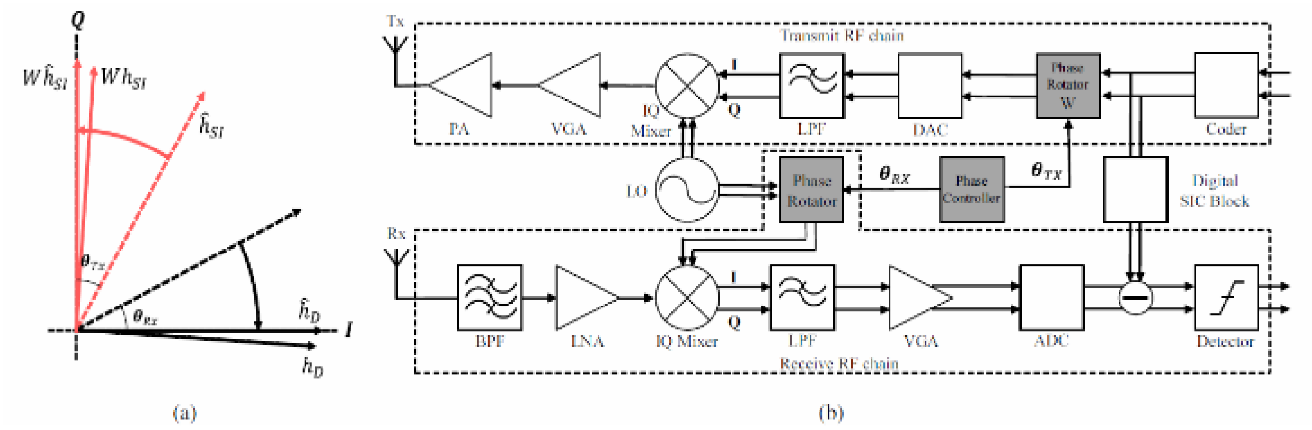

Fig. 1. (a) Basic concept of PR-SIC, where Wh_{SI} indicates self-interference rotated by the phase rotator of transmit RF chain, (b) Block diagram of the proposed FD transceiver. The additional blocks for PR-SIC are shown in gray.

implementations.

2. System Model

We consider a FD system with user equipment (UE) and a base station (BS). Each node has one transmit and one receive antenna. The BS can be equipped with multiple passive SIC techniques, such as directional isolation, absorptive shielding, and cross-polarization [5]. Therefore, the BS can achieve a better passive SIC gain than the UE, allowing us to assume that the BS can suppress self-interference with advanced passive SIC using the analog and digital SIC schemes.[1] Therefore, the focus of this letter will be on the SIC of the UE.

We denote h_{SI} as a self-interference channel from the transmit antenna to the receive antenna at the UE and h_D as a desired channel from the BS to the UE. We also assume that h_{SI} is residual self-interference at the UE after passive SIC. The UE received signal can be written as

$$y = h_D x_D + h_{SI} x_{SI} + n, \tag{1}$$

where x_D and x_{SI} are the signals transmitted from the BS and UE, respectively, with $|x_{SI}^2| = |x_D^2| = 1$, n is additive white Gaussian noise (AWGN) with $\mathcal{CN}(0, \sigma_n^2)$.

To cancel the self-interference, the UE receiver must be able to estimate both h_{SI} and h_D. The estimated channels $\hat{h}_{SI}$ and $\hat{h}_D$ can be presented as [11]

$$\begin{aligned} \hat{h}_{SI} &= (1+\eta_{SI}) e^{j\phi_{SI}} h_{SI}, \\ \hat{h}_D &= (1+\eta_D) e^{j\phi_D} h_D, \end{aligned} \tag{2}$$

where η_{SI} and ϕ_{SI} are the amplitude and phase estimation errors of h_{SI}, respectively. Also, η_D and ϕ_D are the amplitude and phase estimation errors of h_D, respectively. Additionally, ϕ_{SI} and ϕ_D have a range from $-\pi$ to π.

3. Phase Rotator-based SIC

Now let us move on to our proposal for a new analog SIC scheme: phase rotator-based self-interference cancellation (PR-SIC). As shown in Fig. 1(a), the basic idea of the PR-SIC scheme is to direct the desired signal and self-interference signal in an orthogonal direction and then eliminate the self-interference. Specifically, in the receiver chain, the desired signal is laid on the in-phase component. After that, the self-interference is adjusted to the quadrature component by a transmit phase rotator. Finally, the UE decodes the signal (primarily desired term) laid on the in-phase component and ignores the quadrature component.

3.1 System Architecture of the PR-SIC

Fig. 1(b) shows a block diagram of the proposed scheme. It consists of a receive RF chain and a transmit RF chain. In the receive RF chain, the phase controller calculates the angle of rotation θ_{RX} based on the estimated channel information. The rotation angle θ_{RX} can be written as

$$\theta_{RX} = Arg(\hat{h}_D), \tag{3}$$

where $Arg(\cdot)$ is the argument function which gives the angle between the vector and the positive real axis (in-phase axis). The phase controller then sends the information about θ_{RX} to the receive phase rotator. The

[1] This is because only the infrastructure node has enough space to implement directional antennas and lossy materials to attenuate self-interference. In [13], $85dB$ is achieved by $5m$ antenna separation and absorptive shielding. Also, in [2], an average of $91dB$ is achieved by antennas separated in $5m$. Without antenna separation, an average of $71dB$ can be achieved by passive suppression [5].

receive phase rotator, which is placed between the local oscillator and the IQ mixer, rotates the in-phase and quadrature axes by θ_{RX} . After rotating the two axes, the in-phase component is exactly aligned to the desired signal by adjusting the phase of the local oscillator, as shown in Fig. 1(a). Note that these processes are done in the analog domain.

In the transmit RF chain, the angle θ_{TX} is obtained by the phase controller using estimated channel information. The rotation angle θ_{TX} is the angle between the self-interference signal and the orthogonal direction of the desired signal. It can be written as

$$\theta_{TX} = \frac{\pi}{2} - \left\{ Arg(\hat{h}_{SI}) - Arg(\hat{h}_D) \right\}. \tag{4}$$

Using this value, the transmit phase rotator performs a rotation on the self-interference by θ_{TX} . This transmit phase rotator is implemented in the digital domain, because the digital signal is more tractable than the analog signal. Thus, the transmit phase rotator, which makes the desired signal perpendicular to the self-interference signal, can be expressed as

$$W = \frac{\hat{h}_D / \left|\hat{h}_D\right|}{\hat{h}_{SI} / \left|\hat{h}_{SI}\right|} e^{j(\pi/2)} = \frac{h_D \left|h_{SI}\right|}{\left|h_D\right| h_{SI}} e^{j\left(\frac{\pi}{2} + \phi_D - \phi_{SI}\right)}. \tag{5}$$

Note that only one hardware component, the phase rotator of the receive RF chain, is required in the proposed SIC design while conventional SIC requires additional components, such as a digital-to-analog converter (DAC), attenuator, and RF adder [4].

3.2 PR-SIC for High-order Modulation

In order to be able to cancel self-interference, the proposed PR-SIC scheme must give up one dimension in the two-dimensional received signal space. The loss of this dimension means that the PR-SIC cannot detect general quadrature amplitude modulation (QAM) symbols.

There are two ways to address this problem: The first is to have the transmitter use pulse amplitude modulation (PAM) instead of QAM, as the receiver can detect PAM with one-dimensional received space.

The other is a rotated constellation that can detect each QAM symbol with one detection axis [12]. The rotation angle values for each modulation order needed to use this rotated QAM are given in [13].

Using these two modulation, we can achieve same rate as conventional analog SIC schemes which uses QAM. Moreover, if the PR-SIC outperforms the conventional analog SIC in terms of SIC gain, the SINR of the PR-SIC exceeds the SINR of the conventional analog SIC. We will show the environments where PR-SIC with rotated QPSK outperforms the conventional scheme with QPSK in terms of residual self-interference power and the SIR at section 4 and section 5, respectively.

4. Performance Analysis

4.1 Residual Self-interference after processing with the PR-SIC Scheme

With the PR-SIC scheme, the received self-interference can be written as

$$\begin{aligned} W h_{SI} x_{SI} &= \frac{h_D \left|h_{SI}\right| h_{SI}}{\left|h_D\right| h_{SI}} e^{j\left(\frac{\pi}{2} + \phi_D - \phi_{SI}\right)} x_{SI} \\ &= \left|h_{SI}\right| e^{j\left(\frac{\pi}{2} - \phi_{SI}\right)} x_{SI}, \end{aligned} \tag{6}$$

where $h_D = \left|h_D\right| e^{j(-\phi_D)}$, because $\hat{h}_D$ is laid on the in-phase component in Fig. 1(a). When this received self-interference passes the receive RF chain of the PR-SIC scheme, the residual self-interference of the PR-SIC scheme, I_{PR} , is represented as

$$I_{PR} = \left|h_{SI}\right| x_{SI} \cos\left(\frac{\pi}{2} - \phi_{SI}\right). \tag{7}$$

The power of the residual self-interference in (7) can be calculated as follows:

$$\left|I_{PR}\right|^2 = \left|h_{SI}\right|^2 \sin^2 \phi_{SI}. \tag{8}$$

Remark 1 *From (7) and (8), it can be seen that PR-SIC is not influenced by the amplitude error* η_{SI} *, because PR-SIC only uses the phase information about the self-interference channel and the desired signal channel. This means that the amplitude error does not affect the performance of the proposed scheme. Unlike PR-SIC, conventional SIC is degraded by the amplitude error and the phase error.*

4.2 Residual Self-interference after processing with the Conventional SIC Scheme

The conventional SIC scheme estimates the self-interference channel and subtracts it from the received signal. After that, the residual self-interference can be written as

$$I_{conv} = h_{SI} x_{SI} - \hat{h}_{SI} x_{SI} = \left\{1 - \left(1 + \eta_{SI}\right) e^{j\phi_{SI}}\right\} h_{SI} x_{SI}. \tag{9}$$

According to (9), the power of the residual self-interference after the conventional SIC scheme can be expressed as

$$\begin{aligned} \left|I_{conv}\right|^2 &= \left|1 - \left(1 + \eta_{SI}\right) e^{j\phi_{SI}}\right|^2 \left|h_{SI}\right|^2 \left|x_{SI}\right|^2 \\ &= \left|1 - \left(1 + \eta_{SI}\right) \cos\phi_{SI} - i\left(1 + \eta_{SI}\right) \sin\phi_{SI}\right|^2 \left|h_{SI}\right|^2 \\ &= \left\{1 - 2\left(1 + \eta_{SI}\right) \cos\phi_{SI} + \left(1 + \eta_{SI}\right)^2\right\} \left|h_{SI}\right|^2, \end{aligned} \tag{10}$$

where $e^{j\phi_{SI}} = \cos\phi_{SI} + i\sin\phi_{SI}$ by Euler's formula.

4.3 Superior Conditions for the PR-SIC Scheme

In this subsection, we derive superior conditions where the power of the residual self-interference after processing using the PR-SIC scheme is less than or equal to that of conventional SIC scheme with various values of ϕ_{SI} and η_{SI}. The power difference between the residual self-interference of PR-SIC and conventional SIC, $\Delta_{SI}(\phi_{SI}, \eta_{SI})$, can be represented as

$$\Delta_{SI}(\phi_{SI}, \eta_{SI}) = |I_{conv}|^2 - |I_{PR}|^2. \quad (11)$$

By substituting (8) and (10) to (11), we have

$$\begin{aligned}&\Delta_{SI}(\phi_{SI}, \eta_{SI})\\ &= \left\{1 - 2(1+\eta_{SI})\cos\phi_{SI} + (1+\eta_{SI})^2 - \sin^2\phi_{SI}\right\}|h_{SI}|^2\\ &= \left\{\cos^2\phi_{SI} - 2(1+\eta_{SI})\cos\phi_{SI} + (1+\eta_{SI})^2\right\}|h_{SI}|^2\\ &= \left\{\cos\phi_{SI} - (1+\eta_{SI})\right\}^2 |h_{SI}|^2.\end{aligned} \quad (12)$$

Remark 2 *According to (12), the residual self-interference after the PR-SIC is always less than or equal to the residual self-interference from conventional SIC, independent of the channel estimation error accuracy. The first term and the second term are always greater than or equal to zero and then* $\Delta_{SI}(\phi_{SI}, \eta_{SI})$ *is always greater than or equal to zero. The reason for this is that conventional SIC is influenced by both amplitude and phase estimation error, whereas PR-SIC is only affected by phase estimation error.*

Remark 3 *As the estimation error of the channel amplitude increases,* $\Delta_{SI}(\phi_{SI}, \eta_{SI})$ *increases. This can be shown by calculating the partial derivative of* Δ_{SI} *with respect to* η_{SI} *as*

$$\begin{aligned}\frac{\partial\Delta_{SI}}{\partial\eta_{SI}} &= 2|h_{SI}|^2(\eta_{SI} + 1 - \cos\phi_{SI})\\ &= 2|h_{SI}|^2\left(\eta_{SI} + \frac{\phi_{SI}{}^2}{2!} - \frac{\phi_{SI}{}^4}{4!} + \cdots\right) \approx 2|h_{SI}|^2\eta_{SI},\end{aligned} \quad (13)$$

with the Taylor series. From the experimental result [14], we can assume that $\phi_{SI}{}^2$ *is approximately zero.*[2] *The slope of* Δ_{SI} *is then negative when* $\eta_{SI} < 0$ *and positive when* $\eta_{SI} > 0$. *These tendencies show that* Δ_{SI} *has its minimum value at* $\eta_{SI} = 0$ *and increases as* $|\eta_{SI}|$ *increases. This means that as the amplitude error increases, the performance gap between PR-SIC and conventional SIC widens.*

[2] The phase error is smaller than 0.005 radian over a $20MHz$ frequency bandwidth [14].

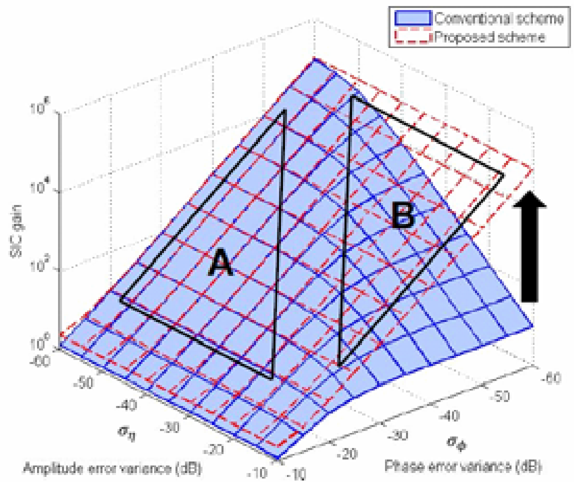

Fig. 2. Self-interference cancellation gain via PR-SIC according to the channel estimation error variance σ_η **and** σ_ϕ **when the residual SIR is** $-50dB$**. The amplitude and phase channel estimation error variance are defined as** σ_η **and** σ_ϕ**.**

5. Numerical Results and Discussion

This section describes the numerical results used to evaluate the performance of the proposed scheme. In the simulations, η_{SI}, η_D, ϕ_{SI}, ϕ_D are denoted as complex Gaussian with zero-mean and variance σ_η, σ_η, σ_ϕ and σ_ϕ, respectively. We assume that ϕ_{SI} and ϕ_D have the same variance and η_{SI} and η_D also have the same variance. In a Wi-Fi system, the transmit power and noise floor level are $20dBm$ and $-90dBm$, respectively [7]. If the self-interference is cancelled by less than $110dB$, some residual self-interference remains, reducing the SINR and throughput. Therefore, we assume that the target SIC gain is $110dB$ and the passive cancellation gain is $60dB$ [4, 7].

Fig. 2 illustrates the SIC gain achieved by changing σ_η^2 and σ_ϕ^2 which are variances of the amplitude error and phase error, respectively. Here, we define the SIC gain achieved with PR-SIC and conventional SIC as

$$\begin{aligned} g_{PR} &= |h_{SI}|^2 / |I_{PR}|^2,\\ g_{conv} &= |h_{SI}|^2 / |I_{conv}|^2.\end{aligned} \quad (14)$$

In region A, the phase error is more dominant than the amplitude error. The conventional scheme and the proposed scheme show almost the same performance in region A. On the other hand, when the amplitude error is

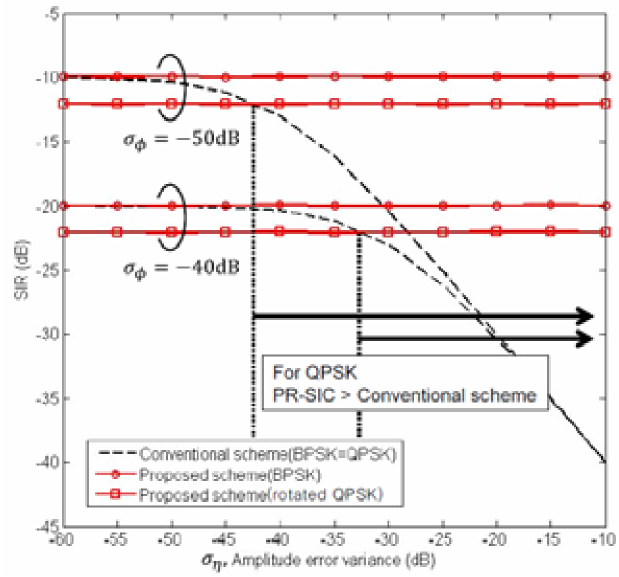

Fig. 3. Signal-to-interference ratio (SIR) for PR-SIC according to the channel estimation error variance σ_η when the residual SIR is $-50dB$ and σ_ϕ is $-50dB$ and $-40dB$. The PR-SIC scheme uses BPSK and rotated QPSK and the conventional SIC scheme uses BPSK and QPSK.

more dominant than the phase error (region B), the SIC gain with PR-SIC is larger than that for conventional SIC. This is due to the fact that the amplitude error only affects the conventional SIC scheme, as addressed in **Remark 3**. Therefore, PR-SIC can produce a larger SIC gain when the amplitude error is more serious than the phase error.

Fig. 3 shows the SIR versus the amplitude error variance σ_η. The phase error, smaller than 0.005 radian over $20MHz$ bandwidth [14], can be roughly converted to $\sigma_\phi = -50dB - 40dB$. The PR-SIC scheme uses BPSK and rotated QPSK and the conventional SIC scheme employs BPSK and QPSK.

In the case of $\sigma_\phi = -40dB$, the SIR gap between the proposed and the conventional scheme widens as σ_η increases. The reason for this is that the proposed scheme is insensitive to the amplitude estimation error, unlike the conventional scheme. This trend also holds in the case of $\sigma_\phi = -50dB$, thus extending the superior region for PR-SIC. From these results, we can see that if the amplitude estimation error is more dominant than the phase estimation error, the PR-SIC is a better solution than conventional SIC because of its robustness to channel estimation error.

6. Conclusion

In this letter, we proposed a PR-SIC scheme to reduce self-interference in the analog domain for FD communication. The PR-SIC scheme orthogonally decomposes the received signal into the desired signal and self-interference and then eliminates the self-interference. We analysed the residual self-interference of the PR-SIC scheme in closed-form expressions and quantified the effects of the channel estimation error. Based on analysis and numerical simulations, we showed that when the channel amplitude estimation suffers from error, the PR-SIC scheme outperforms conventional SIC.

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