Analysis of Desired Receive Signal Impact in Wireless Co-time Co-frequency Full Duplex

Juan Zhou¹, Chao Chen¹*, Yajuan Xue¹, Ying Shen² and Meng He²

¹ College of Communication Engineering, Chengdu University of Information Technology, Chengdu, 610225, China;
² National Key Laboratory of Science and Technology on Communications, University of Electronic Science and Technology of China, Chengdu, 610054, China;
* Email: roosterchen@163.com

Abstract. With self-interference cancellation (SIC), a wireless full duplex terminal is allowed to transmit and receive signal simultaneously in the same frequency band. This paper focuses on the analysis of desired receive signal impact on the radio frequency (RF) SIC performance. The full-duplex system model is first given, and the principle of radio frequency self-interference cancellation is introduced. Then, from the perspective of the convex function, the influence of the desired signal on the RF SIC is analyzed when the total power of the signal after RF SIC is taken as the objective function. It is found that when there is no desired signal, the objective function is a convex function, and the residual self-interference power can converge to the minimum value by the gradient descent method. If the desired signal exists and the channel is constant, the objective function is also a convex function, and the residual self-interference power can also converge to the minimum value. However, in the presence of the desired signal and the channel fluctuates, the target is not a convex function, and the residual self-interference power cannot be converged to the minimum value by the gradient descent method.

1. Introduction

Self-interference problem arises and becomes one of the biggest practical impediments to co-time co-frequency full duplex (CCFD) operation, since a wireless terminal is allowed to transmit and receive simultaneously in the same frequency band [1–3]. To suppress the self-interference, three methods are always considered, including antenna separation, RF cancellation, and digital cancellation [4].

As an important SIC method, the RF cancellation attracts worldwide research interest [5–9]. A novel optical approach to implement RF self-interference cancellation for CCFD communication using phase modulation and optical sideband filtering is proposed in [5]. In [6], a fully integrated technique for wideband cancellation of transmitter (TX) self-interference (SI) in the RF domain is proposed. From [7], it is found that the amplitude and phase errors degrade the SIC performance.

As has been shown in the existing literatures, RF SIC is limited by hardware imperfections and SI modeling inaccuracy. The residual SI after RF cancellation is typically assumed to be well above the desired receive signal power, and therefore the impact of the desired receive signal is normally neglected. However, with a well designed RF SIC scheme, compared to the residual SI, the desired receive signal can be higher and the impact on SIC performance is inevitable.
In this paper, the desired signal impact on the RF SIC performance is analyzed mathematically. Compared with the RF SIC without desired signal, the RF SIC performance with the desired signal is limited by the fluctuation of desired receive signal power.

The system model and the impact on SIC of the RF chain isolation are explained in Section II. In Section III, the proposed scheme for reducing the RF chain isolation impact is proposed. The numerical results are presented in Section IV and Section V concludes the paper.

2. System Model

The system model is shown in figure 1, both the desired signal from the remote terminal and the self-interference signal from the local transmit antenna are received. The RF self-interference signal is estimated with multi-path structure, and then subtracted from the receive signal. Different path has different time delay, phase, and amplitude, which are determined by the baseband unit.

Without loss of generality, local transmit signal $x(t)$ can be described as

$$x(t) = \text{Re}\{b(t)e^{j\omega_c t}\} \quad (1)$$

where $b(t)$ is the complex baseband signal expressed in the RF domain, $\omega_c$ is the carrier frequency, and $\text{Re}(\alpha)$ denote the real part and the imaginary part of $\alpha$. Correspondingly, the received self-interference can be expressed as

$$r_x(t) = \sum_{i=1}^{N} h_i \text{Re}\{b(t - \tau_i)e^{j\omega_c(t-\tau_i)}e^{j\phi_i}\} \quad (2)$$

where $h_i$, $\tau_i$, and $\phi_i$ denote the self-interference channel gain, transmission delay, and phase offset of the $i$-th path, respectively. Let $G = [h_1e^{-j\phi_1}h_2e^{-j\phi_2}...h_Ne^{-j\phi_N}]$ and $D = [b(t - \tau_1)e^{-j\omega_c\tau_1}b(t - \tau_2)e^{-j\omega_c\tau_2}...b(t - \tau_N)e^{-j\omega_cTN}]$, (2) can be rewritten as

$$r_x(t) = \text{Re}\{D^TGe^{-j\omega_c t}\} \quad (3)$$
The RF self-interference signal is estimated for SIC, which can be described as

$$\hat{r}_x(t) = \sum_{k=1}^{K} h_k \text{Re}\{b(t - \tau_k)e^{j\omega_c(t-\tau_k)}e^{j\phi_k}\} \tag{4}$$

where $h_k$, $\tau_k$, and $\phi_k$ denote the estimated self-interference channel gain, transmission delay, and phase offset of the $k$-th path, respectively. $h_k$ and $\phi_k$ are determined at the baseband unit in an adaptive way, and $\tau_k$ is usually manually adjusted by the change of cable length. With $G_r = [h_1 e^{-j\phi_1} \ h_2 e^{-j\phi_2} \cdots h_N e^{-j\phi_N}]$ and $D_r = [b(t - \tau_1)e^{-j\omega_c\tau_1} b(t - \tau_2)e^{-j\omega_c\tau_2} \cdots b(t - \tau_N)e^{-j\omega_c\tau_N}]$, (4) can be rewritten as

$$\hat{r}_x(t) = \text{Re}\{D_r^T G_r e^{-j\omega_c t}\} \tag{5}$$

Similarly, the remote transmit signal $s(t)$ can be written as

$$s(t) = \text{Re}\{b_s(t)e^{j\omega_c t}\} \tag{6}$$

Then the desired receive signal can be given by

$$r_s(t) = \sum_{m=1}^{M} \lambda_m \text{Re}\{b_s(t - \beta_m)e^{j\omega_c(t-\beta_m)}e^{j\theta_m}\} \tag{7}$$

where $\lambda_m$, $\beta_m$, and $\theta_m$ denote channel gain, transmission delay, and phase offset the of desired signal in the $m$-th path, respectively.

The RF SIC mechanism is shown in figure 1, the RF self-interference is rebuilt and subtracted from the whole receive signal. Hence, the residual signal after RF SIC can be obtained by

$$\mu(t) = r_x(t) + r_s(t) - \hat{r}_x(t) + n(t) = I(t) + r_s(t) + n(t) \tag{8}$$

where $n(t)$ is the White Noise and the residual self-interference $I(t)$ is

$$I(t) = \text{Re}\{(D_r^T G - D_r^T G_r)e^{-j\omega_c t}\} \tag{9}$$

Correspondingly, the residual signal power is

$$P_r = E(\|\mu(t)\|^2) \tag{10}$$

Since the self-interference signal, the desired signal and the white noise are independent of each other, (10) can be written as

$$P_r = P_l + P_s + P_n \tag{11}$$

where the residual self-interference power $P_l$ is

$$P_l = E(\|I(t)\|^2) \tag{12}$$

the desired receive power $P_s$

$$P_s = E(\|r_s(t)\|^2) \tag{13}$$

and the white noise power is $P_n = E(\|n(t)\|^2)$.

The purpose of RF SIC is to minimize the residual self-interference power $P_l$. In other words, $D_r^T G$ should be closely approximated by $D_r^T G_r$. In practice, we first determine the transmission delay $\tau_k$ of each path, which is fixed later in the SIC operation. Then the amplitude $h_k$ and phase offset $\phi_k$ are estimated in real time at the baseband unit, so as to minimize the residual self-interference power $P_l$. However, the self-interference and the desired receive signal are mixed together. Hence, $P_l$ is replaced by the residual receive signal power $P_r$, meaning that $h_k$ and $\phi_k$ are determined based on the minimization of $P_r$. 

3
3. Impacts on RF SIC from Desired Signal

As shown in figure 1, the RF self-interference signal is first estimated and then subtracted from the receive signal, so as to get the desired signal. \( P_r \) is used as the criterion for the determination of RF parameters. Based on the minimization of \( P_r \), the impacts on RF SIC from the desired signal are analyzed as follows.

1) No Desired signal.

It means \( P_s = 0 \) and \( P_r = P_I + P_n \). Based on (9), the residual self-interference signal power can be expressed as

\[
P_I = E\{\|D^T \mathbf{G} - D^T_r \mathbf{G}_r\|^2\}
\]  

(14)

For the convenience of analysis, let

\[
D^T \mathbf{G} = CY
\]  

(15)

where \( C = [\text{Re}\{D^T\} + j\text{Im}\{D^T\}, -\text{Im}\{D^T\} + j\text{Re}\{D^T\}] \) and \( Y = [\text{Re}\{\mathbf{G}\}, \text{Im}\{\mathbf{G}\}]^T \). \( \text{Im}(\alpha) \) denotes the imaginary part of \( \alpha \).

Then the residual self-interference signal power can be expressed as

\[
P_I(Y) = E\{\|CY - D^T_r \mathbf{G}_r\|^2\}
\]

\[
= \frac{1}{2} E \left\{ \left( CY - D^T_r \mathbf{G}_r \right)^H \left( CY - D^T_r \mathbf{G}_r \right) \right\}
\]

\[
= \frac{1}{2} \left( P_0 + Y^H \mathbf{R} Y - 2 \text{Re}\{\mathbf{Z} Y\} \right)
\]

(16)

where \( P_0 = E\{(D^T \mathbf{G})^H (D^T \mathbf{G})\} \) is the power of the receive self-interference signal, \( \mathbf{R} = E\{C^H C\} \), and \( \mathbf{Z} = \mathbf{G}^H E\{D^* \mathbf{C}\} \).

Since \( \mathbf{R} \) is autocorrelation and positive semidefinite matrix, \( P_I(Y) \) is convex on \( Y \) [10]. \( Y \) denotes the amplitude and phase offset parameters, hence, \( P_I(Y) \) is convex on the amplitude and phase parameters. With \( P_s = 0 \), the minimization of \( P_I \) is equal to the minimization of \( P_r \). It means that the optimal amplitude and phase offset can be obtained by the minimization of \( P_r \).

In conclusion, when \( P_r = 0 \), with the optimal amplitude and phase parameters \( Y^* \), the residual self-interference signal power can be minimized as \( P_{I,m} = P_I(Y^*) \).

2) With Desired Signal.

It means \( P_s \neq 0 \) and \( P_r = P_I + P_s + P_n \). If the channel gain \( \lambda \) of desired signal from remote node is time-invariant, the signal power \( P_s \) is constant based on (12) and (7). The optimal amplitude and phase parameters can also be achieved by the minimization of \( P_r \). However, in practice the wireless channel is usually time-variant, which means

\[
P_r(Y, t) = P_I(Y) + P_s(t) + P_n
\]  

(17)

If time \( t \) is fixed and \( P_s(t) \) is constant, \( P_r(Y, t) \) is still convex on \( Y \). However, \( t \) is variant during the RF SIC process, and the convexity of \( P_r(Y^*) \) can not be preserved. For the convenience of analysis, gradient descent method is applied to solve the minimization problem. A natural choice for the search direction is the negative gradient. Suppose the RF SIC starts at \( t_1 \) and ends at \( t_2 \), and the \( i \)-dimension of \( Y \) is \( Y_i \). The search direction of \( Y_i \) is calculated as

\[
D(t) \approx \frac{P_r(Y + \kappa Y_i, t_1) - P_r(Y, t_2)}{\kappa}
\]

\[
= \frac{P_I(Y + \kappa Y_i) - P_I(Y) + P_s(t_1) - P_s(t_2)}{\kappa}
\]

\[
= \frac{\Delta P_I(\kappa) - \Delta P_s(t_2 - t_1)}{\kappa}
\]

(18)
where $\kappa$ is the step size, and $\Delta P_s(t_2 - t_1)$ is the variance power of the desired receive signal. The impact of $\Delta P_s(t_2 - t_1)$ on RF SIC is analyzed as follows.

In the first period of RF SIC, since the residual self-interference signal power is much larger than the desired receive signal power, $P_l(Y) \gg |\Delta P_s(t_2 - t_1)|$. With the suitable $\kappa$, $|\Delta P_l(\kappa)| > |\Delta P_s(t_2 - t_1)|$ and the sign of the $D(t)$ is not changed. Hence $P_l(Y)$ can be decreased with the right direction. However, with the decrease of $P_l(Y)$, $|\Delta P_l(\kappa)|$ becomes smaller with the same $\kappa$. When $|\Delta P_l(\kappa)|$ is approximated with $|\Delta P_s(t_2 - t_1)|$, $|\Delta P_l(\kappa)| > |\Delta P_s(t_2 - t_1)|$ can not be preserved and the sign of $D(t)$ can be reversed. In this case, the wrong search direction is used and $P_l(Y)$ can not be decreased, meaning that the minimum $P_l(Y)$ is $|\Delta P_s(t_2 - t_1)|$.

With the descriptions above, the minimum residual self-interference signal power can be given as

$$P_{l,s,m} = \max\{|\Delta P_s(t_2 - t_1)|, P_{l,m}\}$$

(19)

where $P_{l,m}$ is the minimum residual self-interference power without the desired signal described above. When $P_{l,m} > |\Delta P_s(t_2 - t_1)|$, the desired signal impact can be neglected. However, if the desired signal transmitter is near to the local receiver and $P_{l,m} < |\Delta P_s(t_2 - t_1)|$, the RF SIC performance is limited by $|\Delta P_s(t_2 - t_1)|$.

4. Numerical Results

To confirm the theoretical analysis, the simulation platform is developed as follows. 3GPP LTE protocol with 20MHz bandwidth is applied in the CCFD system. The amplitude of desired signal is variant with time. The received self-interference signal power and the received desired signal power are 0dBm and $-30$dBm, respectively.

The self-interference signal channel is first supposed as the single-path channel, and then $P_{l,m} = 0$ under the ideal self-interference channel reconstruction. Figure 2 shows the desired receive signal impact on the residual self-interference signal power. It is found that the residual self-interference signal power can be as less as $-190$dBm without the desired signal. However, in the case of desired receive signal exists, the RF SIC performance is restricted by the desired signal power fluctuation $|\Delta P_s(t_2 - t_1)|$. The residual self-interference signal power $P_l$ is larger than $|\Delta P_s(t_2 - t_1)|$. When $|\Delta P_s(t_2 - t_1)| = -30$dBm, $P_l \approx -25$dBm.

Figure 3 show the desired receive signal impact on the RF SIC performance, considering the multi-path self-interference channel. The multi-path signal channel is established based on the experimental power delay profile, with the delay spread as 200ns. In the RF signal reconstruction, 4-path channel model is used. Since reconstruction channel model is estimated with inevitable error, the self-interference signal can not be cancelled completely even though no desired receive signal. It is found that the residual self-interference signal power $P_l = -36$dBm.
without desired receive signal. However, when the desired receive signal exists, the performance is damaged apparently. When the desired signal power fluctuation \(|\Delta P_s(t_2 - t_1)| = -10\text{dBm}\), \(P_I \approx -7.5\text{dBm}\).

5. Conclusion
In this paper, it is first described that desired receive signal damages the self-interference cancelation performance in CCFD wireless communication system. Through the mathematical analysis, we find that the residual self-interference signal power is limited by the desired signal power fluctuation. In practice, it is usually larger than the desired signal power fluctuation. And it suggests that the study on the method to reduce the desired signal impact is an interesting topic for future research.

Acknowledgments
This work was supported by the National Natural Science Foundation of China under Grant No.61601064.

References
[1] Y. Hua, P. Liang, Y. Ma, A. C. Cirik, and Q. Gao, “A Method for Broadband Full-Duplex MIMO Radio,” *IEEE Signal Process. Lett.*, vol. 19, pp. 793-796, Dec. 2012.
[2] A. Sahai, G. Patel, C. Dick, and A. Sabharwal, “On the Impact of Phase Noise on Active Cancelation in Wireless Full-Duplex,” *IEEE Trans. Veh. Commun.*, vol. 62, pp. 4494-4510, Nov. 2013.
[3] A. Sabharwal, P. Schniter, D. Guo, D. W. Bliss, S. Rangarajan, and R. Wichman, “In-Band Full-Duplex Wireless: Challenges and Opportunities,” *IEEE J. Sel. Areas Commun.*, vol. 32, pp. 1637-1652, Sep. 2014.
[4] M. Duarte, C. Dick, and A. Sabharwal, “Experiment-Driven Characterization of Full-Duplex Wireless Systems,” *IEEE Trans. Wireless Commun.*, vol. 11, pp. 4296-4307, Dec. 2012.
[5] X. Han, B. Huo, Y. Shao, C. Wang, and M. Zhao “RF Self-Interference Cancellation Using Phase Modulation and Optical Sideband Filtering,” *IEEE Photonics technology letters.*, vol. 29, no. 11, pp. 917-920, Jun. 2017.
[6] J. Zhou, T. Chuang, T. Dinc, and H. Krishnaswamy “Integrated Wideband Self-Interference Cancellation in the RF Domain for FDD and Full-Duplex Wireless,” *IEEE Journal of solid-state circuits.*, vol. 50, no. 12, pp. 3015-3031, Dec. 2015.
[7] Z. He, S. Shao, Y. Shen, C. Qing, and Y. Tang, “Performance Analysis of RF Self-Interference Cancellation in Full-Duplex Wireless Communications,” *IEEE Wireless Commun.Lets.*, vol. 3, pp. 405-408, Aug. 2014.
[8] Y. Shen, J. Zhou, and Youxi Tang. “Digital Self-Interference Cancellation in Wireless Co-time and Co-frequency Full-Duplex System,” *Wireless Pers. Commun.*, vol. 82, pp. 2557-2565, Feb. 2015.
[9] E. Ahmed and A. M. Eltawil. “Self-Interference Cancellation Technique for Full-Duplex Systems,” *IEEE Trans. Wir. Commun.*, vol. 14, pp. 3519-3532, Jul. 2015.
[10] S. Boyd and L. Vandenberghe. *Convex Optimization*. Cambridge University Press, 2004.