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Performance of auxiliary antenna-based self-interference cancellation in full-duplex radios

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Dear editor,

Full-duplex (FD) wireless communications, which simultaneously transmit and receive on the same frequency resources, have gained considerable research interest for emerging wireless communication [1, 2]. The primary challenge in implementing the FD transceiver is to handle the strong self-interference (SI). The basis of the radio frequency (RF) SI suppression technique is generating/coupling the reference SI signal and subsequently adding it into the receiver channel to suppress the SI signal [3]. The reference SI signal can be obtained by three methods. For the first method, the reference SI signal can be generated from the baseband, upconverted by a special RF transmit chain [4]. For the second method, the reference SI signal can be coupled after the RF power amplifier (PA) [5, 6]. For the third method, the reference SI signal can be coupled through the antenna in the spatial domain [7]. In some scenarios, especially when the transmit and receive antennas are placed separately with a sizable distance, the third method would have additional advantages over the other two methods. We herein assess the performance of the auxiliary receive antenna (ARA) based the SI suppression scheme as a realization of the third method. As comparison, we also introduce the single-tap RF (STRF) SI suppression scheme as a realization of the second method, where only one receive antenna is used. This study analyzes the factors of the SI signal bandwidth, the SI channel gain ratio, the propagation delay difference, the weighted coefficient, and the correlation coefficient of the intended channels on the performance of the signal-to-noise-plus-interference-ratio (SINR) after SI suppression.

Notation. $\mathrm{E}\{\cdot\}$ and $\mathrm{Re}\{\cdot\}$ denote the expectation operation and the real part of the complex number. $\mathcal{N}\left(\mu, \delta^2\right)$ denotes complex Gaussian process with μ mean and δ^2 variance. $*$ represents conjugate operation. $\mathbb{C}$ denotes the complex domain. $\otimes$ denotes the convolution operation.

System model. Considering a full-duplex system, one antenna is used to transmit signal, while two antennas (denoted as Rx and Rxa) are used to receive the intended signal. For the antennas Rx and Rxa, the received signals $r_1(t)$ and $r_2(t)$ are

$$r_1(t) = h_1(t) \otimes i(t) + g_1(t) \otimes u(t) + n_1(t), \quad (1)$$

$$r_2(t) = h_2(t) \otimes i(t) + g_2(t) \otimes u(t) + n_2(t), \quad (2)$$

respectively, where $i(t)$ represents the local transmit signal; $u(t)$ represents the intended signal transmitted; $n_1(t) \sim \mathcal{CN}\left(0, \sigma_n^2\right)$ and $n_2(t) \sim \mathcal{CN}\left(0, \sigma_n^2\right)$ represent the additive noises; $h_1(t)$ and $h_2(t)$ represent the SI channels for Rx and Rxa, respectively; $g_1(t)$ and $g_2(t)$ represent the intended channels for Rx and Rxa, respectively.

Considering only the line of sight (LOS) SI component, the SI channels can be rewritten as

$$h_1(t) = h_1 \delta(t - \tau_1), \; h_2(t) = h_2 \delta(t - \tau_2), \quad (3)$$

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where h_1 and h_2 denote the amplitudes of the auxiliary and primary SI channels, respectively; τ_1 and τ_2 denote the propagation delays of the auxiliary and primary SI channels, respectively. By adding the weighted signal of $r_2(t)$ to the $r_1(t)$, we can obtain

$$\begin{aligned} y(t) = & h_1 i(t-\tau_1) + w h_2 i(t-\tau_2) + n_1(t) \\ & + w n_2(t) + (g_1(t) + w g_2(t)) \otimes u(t), \end{aligned} \quad (4)$$

where $w \in \mathbb{C}$ denotes the weighted coefficient for the LOS SI signal suppression. For simplification, we assume that the desired channels are Rayleigh and normalized, i.e., $g_1(t) \sim \mathcal{CN}(0,1)$ and $g_2(t) \sim \mathcal{CN}(0,1)$. Let ρ be the correlation coefficient of the intended channels as

$$\rho = \frac{\mathrm{cov}(g_1(t), g_2(t))}{\sqrt{\mathrm{cov}(g_1(t), g_1(t)) \mathrm{cov}(g_2(t), g_2(t))}}, \quad (5)$$

where $\mathrm{cov}(z_1, z_2)$ denotes the covariance. The transmit power of the intended signal $u(t)$ is P_U, i.e., $\mathrm{E}\{|u(t)|^2\} = P_U$. The transmit power of the local transmit signal $i(t)$ is P_I, i.e., $\mathrm{E}\{|i(t)|^2\} = P_I$.

In the SI suppression slot, the remote user remains silent and thus the received signal is

$$\begin{aligned} y_r(t) = & h_1 i(t-\tau_1) + w h_2 i(t-\tau_2) \\ & + n_1(t) + w n_2(t). \end{aligned} \quad (6)$$

Thus, the residual power $y_r(t)$ is

$$\min_{w \in \mathbb{C}} P_r = \min_{w \in \mathbb{C}} \mathrm{E}\left\{ |y_r(t)|^2 \right\}. \quad (7)$$

Optimization. In this section, we present the optimization of the ARA and STRF schemes. We assume that the SI signal $i(t)$ and the additive noises $n_1(t)$ and $n_2(t)$ are uncorrelated. The center operation frequency and the bandwidth of the SI signal $i(t)$ are f_0 and B, respectively. Let $R_{y_r y_r^*}(\tau)$ and $P_{y_r y_r^*}(f)$ denote the autocorrelation and the spectrum density of the $y_r(t)$, respectively. The residual power P_r of the received signal $y_r(t)$ can be expressed as [8]

$$\begin{aligned} P_r = & R_{y_r y_r^*}(0) = \int_{f_0 - \frac{B}{2}}^{f_0 + \frac{B}{2}} P_{y_r y_r^*}(f) \mathrm{d}f \\ = & \int_{f_0 - \frac{B}{2}}^{f_0 + \frac{B}{2}} \Big\{ |h_1|^2 + |w|^2 |h_2|^2 \\ & + 2\cos[2\pi f(\tau_1 - \tau_2) + \angle w] \\ & \cdot |h_1| |w| |h_2| \Big\} I(f) \mathrm{d}f + \sigma_n^2 \left(1 + |w|^2\right), \end{aligned} \quad (8)$$

where $I(f)$ denotes the spectrum density of the SI signal $i(t)$. We assumed that the power spectrum of the SI in the training period is approximately constant. Thus, $I(f) = P_I/B$ and Eq. (8) can be expressed as

$$\begin{aligned} P_r = & P_I \left(|h_1|^2 + |w|^2 |h_2|^2 \right) + \sigma_n^2 \left(1 + |w|^2 \right) \\ & + 2P_I \mathrm{sinc}(B(\tau_1 - \tau_2)) |h_1| |w| |h_2| \\ & \cdot \cos[2\pi f_0 (\tau_1 - \tau_2) - \theta_2 + \theta_1 + \angle w], \end{aligned} \quad (9)$$

where $\mathrm{sinc}(t) = \sin(\pi t)/\pi t$, θ_1, and θ_2 denote the phase of the LOS channel of h_1 and h_2, respectively.

According to (7), the amplitude and phase of w can be obtained by setting the first-order partial derivative of (9) to be zero. To effectively suppress the SI, $|B(\tau_1 - \tau_2)| < \pi$ always stands and it leads to $\mathrm{sinc}(B(\tau_1 - \tau_2)) > 0$. Therefore, $\frac{\partial P_r}{\partial \angle w} = 0$ is equivalent to $\sin[2\pi f_0(\tau_1 - \tau_2) - \theta_2 + \theta_1 + \angle w] = 0$. Thus, we obtain

$$\begin{cases} |w| = \dfrac{P_I |h_1| |h_2| |\mathrm{sinc}(B(\tau_1 - \tau_2))|}{P_I |h_2|^2 + \sigma_n^2}, \\ \angle w = k\pi - 2\pi f_0 (\tau_1 - \tau_2) + \theta_2 - \theta_1, \end{cases} \quad (10)$$

where k is odd if $\mathrm{sinc}(B(\tau_1 - \tau_2)) < 0$, and even if $\mathrm{sinc}(B(\tau_1 - \tau_2)) \geqslant 0$.

Thus, the SINR after SI suppression of the ARA scheme for the narrowband desired signal is approximately calculated as

$$\begin{aligned} \gamma_{\mathrm{ARA}} = & \frac{P_U \left(1 + \left(\frac{P_I |h_1| |h_2| |\mathrm{sinc}(B(\tau_1 - \tau_2))|}{P_I |h_2|^2 + \sigma_n^2} \right)^2 \right)}{P_I |h_1|^2 + \sigma_n^2 - \frac{P_I^2 |h_1|^2 |h_2|^2 \mathrm{sinc}^2 (B(\tau_1 - \tau_2))}{P_I |h_2|^2 + \sigma_n^2}} \\ & + \frac{2P_U \mathrm{Re}\left(\rho \frac{P_I |h_1| |h_2| \mathrm{sinc}(B(\tau_1 - \tau_2))}{P_I |h_2|^2 + \sigma_n^2} \mathrm{e}^{\mathrm{j}2\pi f_0 (\tau_1 - \tau_2)} \right)}{P_I |h_1|^2 + \sigma_n^2 - \frac{P_I^2 |h_1|^2 |h_2|^2 \mathrm{sinc}^2 (B(\tau_1 - \tau_2))}{P_I |h_2|^2 + \sigma_n^2}}. \end{aligned} \quad (11)$$

Similarly, the SINR γ_{STRF} after SI suppression for the narrowband desired signal is

$$\gamma_{\mathrm{STRF}} = \frac{P_U}{P_I |h_1|^2 + \sigma_n^2 - \frac{P_I^2 |h_1|^2 |\tilde{h}_2|^2 \mathrm{sinc}^2 (B(\tau_1 - \tau_2))}{P_I |\tilde{h}_2|^2 + \sigma_n^2}}. \quad (12)$$

where $|\tilde{h}_2|^2$ represents the single RF tap channel.

Performance comparisons. According to (11), if the propagation delay difference $\Delta\tau = 0$, $P_I |h_2|^2 \gg \sigma_n^2$ and $|h_1|^2 / |h_2|^2 = |h_1|^2 / |\tilde{h}_2|^2$, we obtain $\gamma_{\mathrm{ARA}} = \frac{2P_U(1+\mathrm{Re}(\rho))}{\sigma_n^2}$ and $\gamma_{\mathrm{STRF}} = \frac{P_U}{\sigma_n^2}$. Hence, the SINR after SI suppression for the ARA scheme is almost zero when the correlation coefficient $\rho = -1$ and the SINR nearly doubles

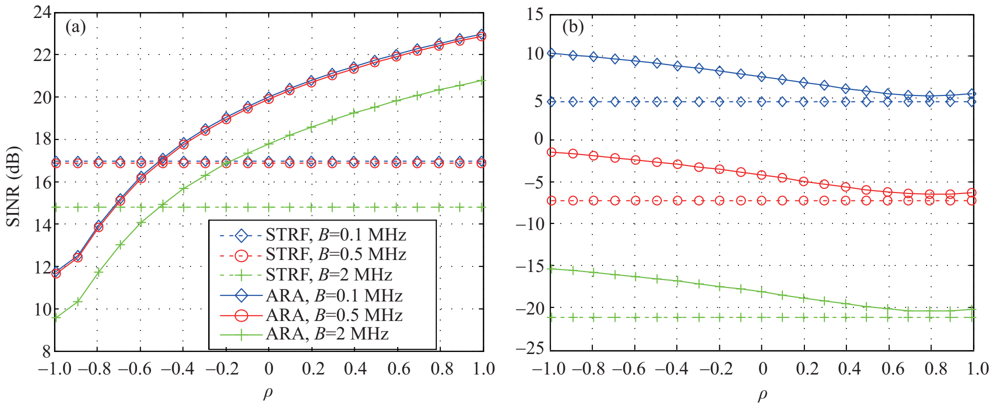

Figure 1 (Color online) The output SINR after SI suppression vs. the correlation coefficient of the intended channels ρ. SNR = 20 dB, $|h_1|^2/|h_2|^2 = |h_1|^2/|\tilde{h}_2|^2 = 1$. (a) $\Delta\tau = 0.01$ ns; (b) $\Delta\tau = 1$ ns.

the STRF scheme when $\rho = 1$. This result indicates that the correlation coefficient ρ decides whether the ARA scheme can outperform the STRF scheme.

In particular, when $\rho = 0$ with $P_I|h_1|^2 \gg \sigma_n^2$, $P_I|\tilde{h}_2|^2 \gg \sigma_n^2$ and $P_I|h_2|^2 \gg \sigma_n^2$. The SINRs γ_{STRF} and γ_{ARA} after SI suppression for the STRF and ARA schemes are

$$\gamma_{\text{STRF}} \approx \frac{\frac{P_U}{P_I|h_1|^2}}{1-|\text{sinc}\left(B\left(\tau_1-\tau_2\right)\right)|^2},$$
$$\gamma_{\text{ARA}} \approx \frac{\frac{P_U}{P_I|h_1|^2}\left(1+\frac{|h_1|^2|\text{sinc}(B(\tau_1-\tau_2))|^2}{|h_2|^2}\right)}{1-|\text{sinc}\left(B\left(\tau_1-\tau_2\right)\right)|^2}, \quad (13)$$

respectively. This indicates that γ_{ARA} is always larger than γ_{STRF}.

Simulations. The self-interference-to-noise-ratio (INR) of the received signal at the Rx antenna is 90 dB, i.e., $P_I|h_1|^2/\sigma^2 = 10^9$. To study the impact of the correlation coefficient ρ of the intended channels on the output SINR after the SI mitigation, we consider a simplified scenario, where the correlation coefficient ρ of the intended channels varies from -1 to 1. From Figure 1(a), the output SINR of the ARA scheme outperforms the STRF scheme for the correlation coefficient $\rho \geqslant -0.5$. From Figure 1(b) the ARA scheme always outperforms the STRF scheme. This result means that we can obtain a better output SINR if we precisely adjust the correlation coefficient ρ. As the correlation coefficient ρ is influenced by the near-field reflectors and may be changed when the near-field reflectors move, it is difficult to precisely adjust ρ to the desired value. Thus, it is worth decreasing the correlation coefficient ρ of the intended channels.

Conclusion. Herein, the performance of the auxiliary receive antenna (ARA) scheme is analyzed and compared with the single-tap RF (STRF) scheme. The closed-form expressions of the output SINR after SI suppression are provided. In particular, if the channel correlation of the intended signals is zero, the ARA always outperforms the STRF scheme. The analysis and simulation results show that the channel correlation between the primary and auxiliary receive antennas for the intended signals should be set to low for a well-intended signal receiving.

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