

Self-Interference Cancellation Techniques for Full-Duplexing Mobile Communication Systems

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Abstract—This paper investigates self-interference cancellation (SIC) techniques for enabling full-duplex (FD) operations in mobile communication systems. We explore several SIC strategies: analog beamforming to suppress direct-path SI, digital baseband SIC based on channel estimation, SIC with power amplifier (PA) nonlinearity estimation, and digital beamforming for reflected-path SI nulling. Simulation results confirm that these combined approaches effectively suppress SI below the noise floor, demonstrating the feasibility of practical FD deployments in future mobile networks.

Keywords—full-duplex, self-interference, digital cancellation, beamforming

I. INTRODUCTION

Several full-duplex variants are considered in the evolution of 5G-Advanced systems. Sub-Band Full Duplex (SBFD) allows downlink (DL) and uplink (UL) operations within different subbands of the same time slot [1]. This approach has the potential to double spectral efficiency, increase uplink coverage and reduce latency compared to conventional half-duplex systems. However, the practical deployment of full-duplex systems is hindered by the presence of self-interference (SI) — the strong transmitted signal that leaks into the receiver and can overwhelm the desired weak received signal. In-Band Full Duplex (IBFD) extends this concept further by performing simultaneous DL and UL operations over the entire bandwidth, presenting the highest SI challenges.

To mitigate SI, traditional approaches often rely on adaptive filtering techniques [2,3]. It requires a orthogonalization transformation for rapid adaptation. Furthermore, in MIMO systems, it is difficult to estimate the filter coefficients by using the received signals from multiple transmit antennas. However, as the channel estimation methodology used in many mobile communication systems, we can estimate the SI channel to cause the interference to the receiver by transmitting a known reference signal in a non-scheduled slot or symbols in a slot, and then the SI signal can be cancelled by using the transmit signal and the estimated channel.

In this paper, we consider SI cancellation (SIC) techniques; analog beamforming with direct-path SI nulling, digital SIC based on channel estimation and digital beamforming with time varying SI nulling, and show that the strong SI can be reduced below the noise floor by simulations.

II. SYSTEM MODEL

We consider a base station implementing full-duplexing operations in a TDD-based 5G NR system, as in Fig. 1. The base station transmits DL signals and receives UL signals

simultaneously within separate frequency subbands in case of SBFD or within the whole band in case of IBFD.

The transmit and receiving antenna arrays are separated so that the SI from the transmit array to the receiving array can be reduced. Each antenna array has a configuration of $(M, N, P) = (8, 4, 2)$ as shown in Fig. 2, where M denotes vertical elements per port, N the number of horizontal spatial ports, and P the number of polarizations. The base station performs analog beamforming per antenna port using phase shifters across M elements and digital beamforming over ports using $N_{port}=NP$ RF branches. It uses the baseband output (after baseband SB or FB filtering) or the PA coupling output as reference transmit signals for SI estimation and cancellation. In case of using PA output, the reference transmit signal includes the nonlinear components raised by RF nonlinearity (especially, PA).

The self-interference channel consists of two components as shown in Fig. 2: a direct coupling path between transmit and receive antenna arrays modeled by a near-field propagation channel with distant-dependent phase [4], and a reflected path due to objects near antenna arrays modeled by a multipath fading channel. We use a modified 3GPP CDL-D channel model [5] for the reflected path and consider the reflected-path loss so that the received power from the reflected path can be similar to the direct-path power reduced by antenna separation, antenna gain pattern, and analog beamforming at antenna arrays.

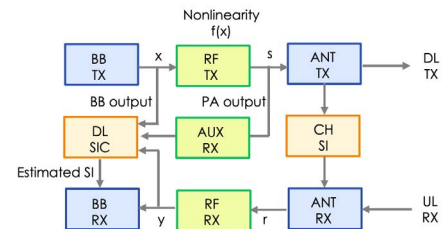


Fig. 1. System model for full duplexing and self-interference cancellation.

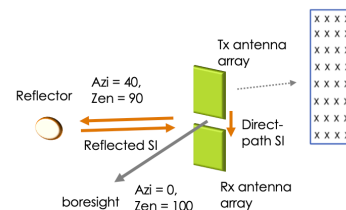


Fig. 2. Antenna array and SI channel.

Table I shows the system parameters used for our simulation. Total transmit power is 55 dBm over all 8 ports and thus a total SIC range of 141 dB at the receiver is required for an interference-to-noise (INR) ratio of -6 dB (1-dB desensitization) after SIC.

TABLE I. SYSTEM PARAMETERS

Parameters	Value	Note
Carrier frequency	4 GHz	In FR1
Carrier bandwidth	100 MHz	
Subcarrier spacing	30 kHz	
No. used subcarriers	3276	$=N_{used}$
No. symbols in a slot	14 symbols	
PRUs, DL:G:UL:G:DL	104:5:55:5:104	For SBFD
PA saturation power	46 dBm	For each ant. element
PA average output power	37 dBm	Backoff 9 dB
Port average power	46 dBm	8 PAs per tx port
Total transmit power	55 dBm	8 ports
Noise power	-80 dBm	8 LNAs, NF=5dB
Antenna array (M, N, P)	(8, 4, 2)	For each array
Antenna element pattern	Bell-shape in [4]	Max. gain = 8 dB
Array isolation loss	20 dB	By ant. separation
Reflected-path loss	90 dB	

III. SELF INTERFERENCE CANCELLATION TECHNIQUES

A. Analog Beamforming for Direct-Path SI Nulling

Analog beamforming (ABF) is a basic technique for suppressing self-interference from the direct path. ABF appropriately configures the phase weights across the antenna elements at each transmit and receive port, and performs spatial nulling to direct SI path while maintains beamforming to a designated spatial direction. In our simulation, zero-forcing (ZF) beamforming is employed to simultaneously maximize gain in the desired direction (zenith 105°) and minimize gain toward the direct SI path (zenith 0° and 180°).

The transmit ZF ABF weights can be obtained by $\mathbf{Z}_t = \mathbf{V}_t[(\mathbf{V}_t^H \mathbf{V}_t)^{-1}]^H$ where $\mathbf{V}_t = [\mathbf{V}_{tu}, \mathbf{V}_{tr}]$, $\mathbf{V}_{tu}$ is obtained by a SVD (singular value decomposition) $\mathbf{H}_{tu} = \mathbf{U}_{tu} \mathbf{\Sigma}_{tu} \mathbf{V}_{tu}^H$ of the channel for the beam-forming direction, and $\mathbf{V}_{tr}$ is obtained by a SVD $\mathbf{H}_{tr} = \mathbf{U}_{tr} \mathbf{\Sigma}_{tr} \mathbf{V}_{tr}^H$ of the channel for the beam-nulling direction. The beam-forming (BF) and beam-nulling (BN) channels can be set by using a steering vector $\mathbf{a}(\theta) = [1, e^{j2\pi \frac{d}{\lambda} \sin \theta}, \dots, e^{j2\pi \frac{d}{\lambda} (M-1) \sin \theta}]^H$ where $\theta = 105^\circ$ (with down-tilting 15°) for BF and 180° for BN. The receiving ZB ABF weights can be also obtained by a similar way with $\theta = 100^\circ$ for BF and 0° for BN. Fig. 3 shows transmit beam patterns configured by ABF over $M=8$ vertical antenna elements in case of non-quantized $\mathbf{Z}_t$ and 6-bit quantized phases. The ABF beam patterns show the largest gain to BF direction and the nulling or suppression at BN direction.

Fig. 4 shows signal spectrums of signal transmitted from a transmit port, and received by a receiving port when using the DL subbands. The transmit power level of 55 dBm over all transmit ports is reduced to the received power level (RX SI port in Fig.4) of about -36 dBm at a receive port due to the transmit/receive ABF, the bell-shape gain pattern of antenna elements and the additional direct-path SI suppression by antenna array isolation of 20 dB.

B. SI Cancellation based on SI Channel Estimation

To suppress the residual SI not eliminated by ABF, digital cancellation is performed in the baseband, based on SI channel estimation. The base station transmits reference signals (RS) such as Zadoff-Chu (ZC) sequences covered with Walsh codes across antenna ports to enable per-port channel estimation, in symbols in a slot not used for both DL and UL transmission. In our simulation, eight RS symbols are transmitted in a SI channel estimation slot. A ZC sequence with a length of N_{used}/S_{freq} is used for a RS symbol and spread in time and frequency domain by Walsh codes with a length $N_{port}=S_{freq}S_{time}=1 \times 8$.

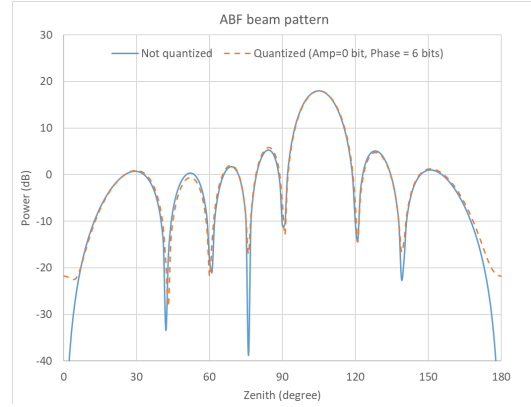


Fig. 3. Antenna array and SI channel.

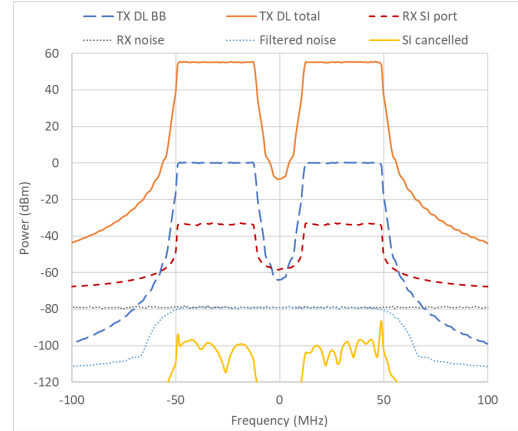


Fig. 4. Transmit and receiving signal spectrums in SBFD.

The SI channel estimation and SIC can be processed in time or frequency domain before or after the FFT in OFDM receiving processes. In case of time-domain SIC, a SI channel vector with a length of L between transmit port i and receive port j is estimated by a well-known least-square (LS) estimator $\mathbf{h}_{j,i} = (\mathbf{S}_i^H \mathbf{S}_i)^{-1} \mathbf{S}_i^H \mathbf{y}_j$ where $\mathbf{y}_j$ is the received signal vector at port j and $\mathbf{S}_i$ is a matrix with cyclic-shifted columns of the transmit signal (PA coupling output) vector $\mathbf{s}_i$ at port i . The time-domain SIC at receive port j is accomplished by $\mathbf{y}_{j,SIC}(t) = \mathbf{y}_j(t) - \sum_{l=0}^{NP-1} \sum_{i=0}^{L-1} \mathbf{s}_i(t) \mathbf{h}_{j,i}(t-l)$ using the estimated channel $\mathbf{h}_{j,i}(l)$, transmit PA output signal $\mathbf{s}_i(t)$ and received signal $\mathbf{y}_j(t)$.

For the frequency-domain SIC, the SI channel at a subcarrier f can be simply estimated by $H_{j,i}(f) = Y_j(f)/S_i(f)$ where $Y_j(f)$ and $S_i(f)$ are the received signal and the reference transmitted signal after FFT, respectively. The

received signal after SIC is obtained by $Y_{j,SIC}(f) = Y_j(f) - \sum_{i=0}^{NP-1} H_{j,i}(f)S_i(f)$.

In Fig. 4, the SI power after the time-domain SIC is lower than the noise power level -80 dBm and the interference-to-noise power ratio (INR) is -21.9 dB in DL SB and -41.9 dB in UL SB. The estimation performance of the time-domain SIC is sensitive to the estimated SI channel length and a real SI channel length. Fig. 5 shows the SI power levels after the frequency-domain SIC in case of IBFD (using the whole band for DL) and the INR can be achieved to -10.9 dB.

It is noted that the SIC range achieved by a baseband digital SIC is practically restricted to a ADC dynamic range of typically 60 dB. Therefore, the SI level should be reduced by a RF SIC before ADC if a ratio of received power to noise power is larger than the ADC range.

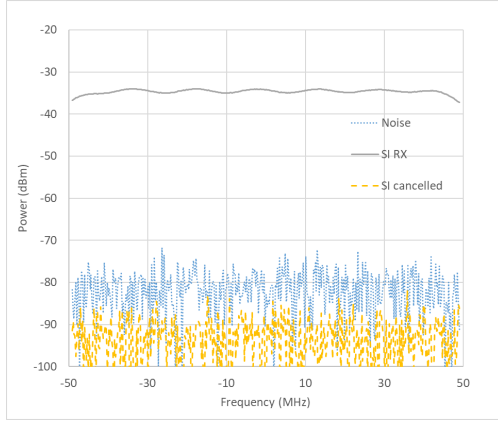


Fig. 5. Frequency-domain SIC spectrums in IBFD.

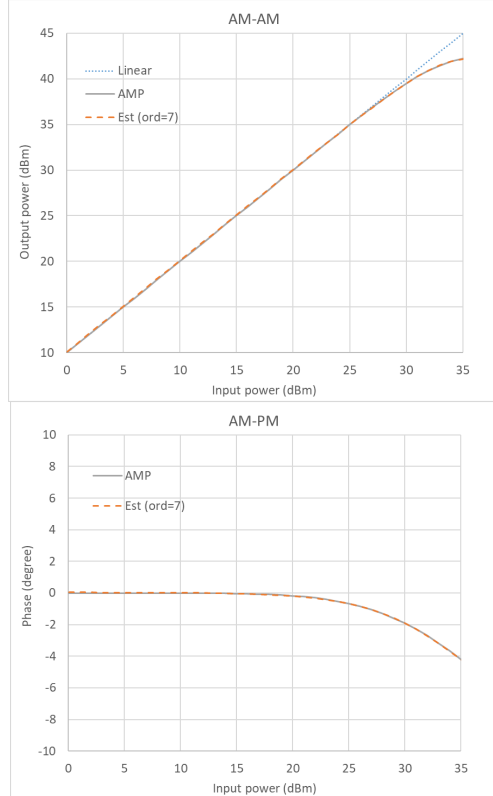


Fig. 6. PA nonlinearity estimation by order-7 Taylor series.

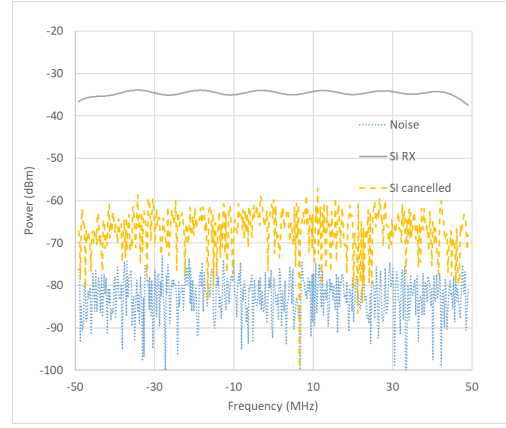


Fig. 7. Frequency-domain SIC spectrums in IBFD using baseband output and nonlinearity estimation.

C. SI Cancellation with Nonlinearity Estimation

In the previous sections, the reference transmit signals for SI estimation and cancellation was the PA output in Fig. 1. To use the baseband output for the reference transmit signals, the PA nonlinearity should be estimated to cancel SI signals with nonlinear components. In this paper, the AUX and Rx RF nonlinearity is ignored because the rising power by RX nonlinearity is smaller than noise power.

The PA nonlinearity can be modeled as a memoryless polynomial function, typically using odd-order Taylor series, $s(t) = \sum_{p=1}^P a_p x^p(t)$ where $x^p(t) = |x(t)|^{p-1}x(t)$. The polynomial coefficients a_p can be estimated using a LS estimator $\mathbf{a} = (\mathbf{x}^H \mathbf{x})^{-1} \mathbf{x}^H \mathbf{s}$ between the baseband output $\mathbf{x}$ and the observed signal $\mathbf{s}$ through the auxiliary path. The SI transmit signal is estimated by $s(t) = \sum_{p=1}^P \tilde{a}_p x^p(t)$ using the estimated coefficients $\tilde{a}_p$ for SIC.

Fig. 6 shows AM/AM and AM/PM characteristics of the estimated PA by the Taylor series with order $p=7$. In our simulation a modified Rapp model [6] is used for the PA. Fig. 7 shows the SIC signal power levels before and after the frequency-domain SIC with PA nonlinearity estimation. The INR after SIC is 13.1 dB with a SIC range of 30 dB and higher than noise level because of the nonlinearity estimation error. It requires very high-order high accuracy to reduce residual interference below the noise floor — often necessitating 80 dB modeling precision beyond a typical ADC dynamic range 60 dB. In contrast, directly capturing the PA output through an auxiliary path bypasses the need for nonlinearity estimation and offers more robust cancellation, achieving a SI power level lower than noise in Fig. 5 even though it requires RF coupling and AUX RF paths.

D. Digital Beamforming for Reflected-Path SI Nulling

With an ideal SI channel estimation, the SI can be perfectly cancelled by the time or frequency domain SIC. However, the SI channel estimation error causes the residual SI. Moreover, mobile reflectors introduce SI components that vary over time. To address this, digital beamforming (DBF) techniques are applied over transmit and receive ports. DBF uses the covariance of the received SI signal across antenna ports to identify dominant spatial components. An eigenvalue decomposition (EVD)-based beamformer then suppresses these directions.

In the frequency-domain after receiver FFT, the transmit covariance matrix of SI channel over transmit and receive ports can be decomposed by $\mathbf{R}_{tx} = \mathbf{H}_{SI}^H \mathbf{H}_{SI} = \mathbf{Q}_{tx} \mathbf{D}_{tx} \mathbf{Q}_{tx}^H$ where $\mathbf{H}_{SI} = [H_{j,i}(f)]$ is the SI channel matrix estimated in frequency domain. To nullify the DBF beam to the SI direction, the precoding matrix can be obtained by $\mathbf{P}_{tx} = \mathbf{Q}_{tx,null} \mathbf{Q}_{tx,null}^H \mathbf{P}_{DL}$, where $\mathbf{P}_{DL}$ is a precoding matrix for DL transmission, and $\mathbf{Q}_{tx,null}$ is a matrix for null-space projection and configured by columns of $\mathbf{Q}_{tx}$ with $r_{tx,n}$ smallest eigenvalues. The null rank $r_{tx,n}$ is selected by $r_{tx,n} = r_{tx} - r_{tx,SI}$ based on the non-neglecting SI rank $r_{tx,SI}$.

In the similar way as in the transmit DBF, the receive covariance matrix of SI channel can be decomposed by $\mathbf{R}_{rx} = \mathbf{H}_{SI} \mathbf{H}_{SI}^H = \mathbf{Q}_{rx} \mathbf{D}_{rx} \mathbf{Q}_{rx}^H$. To nullify the SI direction at the receiver, the combining weight matrix over the receive ports can be obtained by $\mathbf{W}_{rx} = \mathbf{W}_{UL} \mathbf{Q}_{rx,null} \mathbf{Q}_{rx,null}^H$, where $\mathbf{W}_{UL}$ is a combining matrix for UL receiving, and $\mathbf{Q}_{rx,null}$ is a matrix for null-space projection and configured by columns of $\mathbf{Q}_{rx}$ with $r_{rx,n}$ smallest eigenvalues.

It is difficult to nullify the direct-path SI from vertical direction with horizontally angular spreading by using horizontal DBF ports. Therefore, the DBF needs to focus on the time-varying reflected-path SI only. A circuit-based RF SIC or digital pre-SIC before the digital SIC can cancel the first-path SI (i.e., direct path). In our simulation, the time-domain pre-SIC before the baseband receiving filtering is considered for the direct-path SIC. After the pre-SIC, the residual SI channel is estimated for the digital SIC and the transmit and receive covariances are estimated for DBF from received SI RS signals where the first-path SI component is sufficiently cancelled.

To estimate and cancel time-varying SI, an online RS symbol is needed to be transmitted periodically. However, to estimate the time-varying SI within a slot, more SI RS symbols are required and it make a large overhead not to accept in terms of a system efficiency. Therefore, it is desirable to use a periodical SI RS symbol for relatively slowly-changing spatial covariance for DBF. In our simulation, an online RS symbol for each transmit port is spread by spreading codes in frequency domain to distinguish the transmit ports and transmitted in the last symbol in a slot every period.

Fig. 8 shows the DBF beam pattern with nulling. The beam patterns by DBF over horizontal ports successfully nullify the reflector direction of azimuth 40° . Table II shows the SIC values when the DBF is used for the time-varying reflected SI with a reflector moving speed of 5 km/h. Without DBF, the SI power cannot be reduced to below the noise level because of SI channel estimation error in the digital SIC. The time-varying reflected SI can be effectively suppressed through transmit and/or receiving DBF nulling with null-space projection.

IV. CONCLUSIONS

To cancel self-interference (SI) from the simultaneous transmission and reception in full-duplexing mobile

communication systems such as SBFD or IBFD, this paper presented several SIC schemes including analog beamforming for direct-path SI nulling, digital baseband cancellation through SI channel estimation, RF nonlinearity estimation, and digital beamforming for reflected-path time-varying SI suppression. Simulation results confirm that those SIC techniques contribute significantly to SI reduction, with the combined system capable of suppressing interference below the receiver noise floor.

Future work may extend toward hardware prototyping for experimental validation.

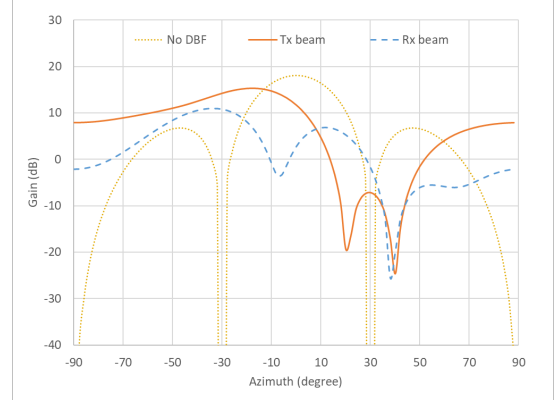


Fig. 8. Frequency-domain SIC spectra in IBFD using baseband output and nonlinearity estimation.

TABLE II. SI CANCELLATION FOR TIME-VARYING SI.

INR (dB)	IBFD INR (dB)	SBFD DLSB	SBFD UL5B
Without DBF	27.7	27.8	-9.6
With DBF	-6.1	-6.3	-33.3

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