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A Digital Self-interference Cancellation algorithm based on Spectral Estimation in Co-time Co-frequency Full Duplex System

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***Abstract*—In a Co-time Co-frequency Full-duplex (CCFD) system, the ability of Self-interference Cancellation (SIC) is limited if we use negative SIC or radio frequency SIC alone, so the residual Self-Interference Signal (SIS) needs to be further cancelled in digital domain. This paper proposed a digital Self-interference Cancellation algorithm based on spectral estimation, via establishing spectral estimation SIS model, we can analyze the spectrum of the SIS and digital transmitted signal. Then reconstruct the SIS and self-adaption cancellation via the second-order cyclic statistic information of signals. The simulation result shows that the proposed algorithm performance and convergence can effectively improved.**

Keywords—Full Duplex, Self-Interference Signal, Digital SIC, Spectral Estimation.

I. Introduction

The Co-time Co-frequency Full-duplex (CCFD) communication systems receive and transmit signals at the same time and frequency. Compared with half-duplex communication systems, the full-duplex systems have significant advantages in throughput, wireless access with collision avoidance, reducing congestion and so on.

The biggest challenge of the full-duplex system is that the interference signal power caused by the proximal transmitting antenna is larger than useful signal, and the useful signals fail to analog-digital converse accurately. Therefore, we need to eliminate SIS by effective interference cancellation technology, and improve the efficiency of the frequency spectrum.

There are negative SIC and positive SIC in the SIC technology. Negative SIC technology can achieve 20-40dB elimination ability by directional inhibition [1-3], antenna isolation [4-5], etc. Positive SCI is divided into analog SIC and digital SIC. Analog SIC can achieve 20-30dB elimination ability by time domain cancellation [6-8] and spatial domain cancellation [9-11]. Digital SIC can eliminate the residual SIS of 10-20dB by SIS reconstruction [12-14], adaptive filtering [15-17], etc. In [18], an adaptive digital SIC algorithm based on channel estimation is presented, via rough estimation and adaptively tracking in the self-interference channel to make channel estimation accurately. However, using rough estimation based on training sequence before communication seriously impact the timeliness, and limited the application scope of full duplex system because the nodes need agree sending steps with training sequence before the communication. In [12], an adaptive baseband cancellation technology is considered, which increased the performance of the digital SIC via reducing the estimation error. However, the algorithm performance is affected by the radio frequency (RF) and needs further research.

In this paper, we propose a digital SIC algorithm based on spectral estimation. The algorithm could effectively eliminate the interference via spectrum estimation and adaptive adjustment, and had a better convergence and smaller computational complexity. Full-duplex system and signal processing will be introduced in Section Ⅱ. Section Ⅲ presents a spectral estimation model, and analyzes the spectrum of the SIS and digital transmitting signal, then reconstruct and eliminate SIS. The estimation error is reduced by adaptive adjustment. The simulation and analysis are provided in Section Ⅳ. Finally, conclusions and discuss are made in Section Ⅴ.

II. CO-TIME CO-FREQUENCY FULL-DUPLEX

As shown in figure 1, in the CCDF system of single-input single-output (SISO), take the local transceiver as an example, the digital transmitting signal $s(n)$ through digital-to-analog converters (DAC) will turn into RF transmitting signal $s(t)$ and will be sent by transmitting antenna. At the receiving antenna, the receiving signal not only includes the desired signal $r_U(t)$ from remote device, but also includes the SIS $r_I(t)$ from local transmitter because the transmitter and receiver are working at the same time and frequency,. The interference signal can be eliminated in different modules of receiving link. Here, we mainly research on digital SIC.

The local receiver received signals $r_0(t)$ is:

$$r_0(t)=r_U(t)+r_I(t)+w(t) \tag{1}$$

Where, $r_U(t)$ is the desired signal from remote device, $r_I(t)$ is the SIS from local transmitter, $w(t)$ is noise, we assume it a stability white noise.

After amplitude modulation and phase modulation of the RF signal $s(t)$, we can process the RF self-interference cancellation via the RF reconstitution signal $r_1(t)$:

$$r(t) = r_0(t) - r_1(t) \tag{2}$$

Where $r(t)$ is the signal after RF cancellation. We obtain the digital receiving signals $r(n)$ after ADC. Next, we focus on digital SIC with digital receiving signals $r(n)$.

The interference signal reconstruction, as one of the digital SIC significance step, not only needs a process of range and frequency, but also needs a phase recovery.. Considering the imperfections of the device, such as the nonlinear distortion of power amplifier, phase noise and quantization noise[16], the process will compensate the phase error and overcome the phase jitter caused by carrier frequency offset[19].

The second-order statistics information (such as correlation function and power spectrum) does not contain the phase information which the reconstruct SIS needs. The second-order cyclic statistics of cycle signal (such as the cyclic autocorrelation function and spectrum correlation dense (SCD)) contain the phase characteristic used to phase recovery which the second-order statistics information does not have.

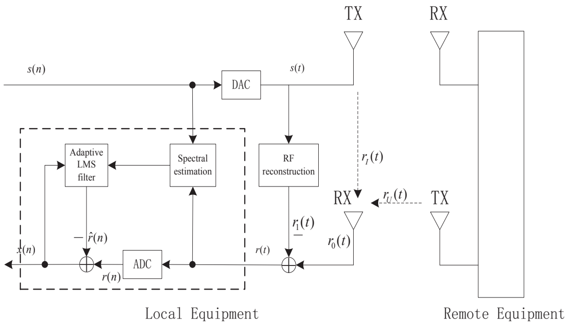

Fig.1 CCDF system model

III. DIGITAL SIC ALGORITHM BASED ON SPECTRAL ESTIMATES

A. *Established spectral estimates model*

Frist, we need super-sampling of the RF signals $r(t)$, so that the signal will be discrete cycle stationary process with smooth circulation characteristics after sampling :

$$r(t) \overset{\text{super-sampling}}{\rightarrow} r(nT_s) \tag{3}$$

Where T_s is sample rate.

The cycle autocorrelation function of cycle signal $r(nT_s)$ estimated by[19]:

$$\hat{R}_r^\beta(mT_s) = \frac{1}{2N+1}\sum_{n=-N}^{N} r(nT_s + mT_s) r^*(nT_s) e^{-j2\pi\beta(n+\frac{1}{2})T_s} \tag{4}$$

The SCD of $r(nT_s)$ is estimated by[19]:

$$\hat{S}_r^\beta(jw) = \sum_{m=-M}^{M} \hat{R}_r^\beta(mT_s) e^{-jwmT_s} \tag{5}$$

The estimation error of cyclic autocorrelation function needs as small as possible, it must meet $N \gg T/T_s$, $N \gg M$. In order to ensure the estimates error of SCD is small enough, M must be large enough[19].

For digital signal $s(n)$, the power spectral density (PSD) is given by:

$$S_s(jw) = \sum_{k=-\infty}^{+\infty} R_s(k) e^{-jwkT} \tag{6}$$

Where, $R_s(k)$ is autocorrelation function of $s(n)$.

Assuming that $w(n)$ is white noise, of which the PSD is:

$$S_w(jw) = N_0 \tag{7}$$

Where N_0 is variance of $w(n)$.

B. *Reconstruction and cancellation of self-interference information*

From the formula (5), (6) and (7), we can obtain the SCD $\hat{S}_r^\beta(jw)$ of RF signal, the PSD $S_s(jw)$ of digital signal $s(n)$, and the PSD $S_w(jw)$ of noise:

$$S_x^\beta(jw) = \frac{1}{T} H(jw + j\pi\beta) H^*(jw - j\pi\beta) S_s(jw + j\pi\beta) \cdot e^{-j2\pi\beta t_0} + S_w(jw) \tag{8}$$

It is concluded that the weight vector $\mathbf{H}$ of interfere reconstruction filtering, including range coefficient $\mathbf{A}$, delay factor $\boldsymbol{\tau}$ and phase coefficient $\boldsymbol{\theta}$. Where, $H(jw)$ is the reconstruction filter system function.

Filtering the digital signal $s(n)$ Via reconstruction filter, then we can obtain the reconstructing signal of digital receiving signals $r(n)$:

$$\hat{r}(n) = s(n) \otimes h(n) + w(n) \tag{9}$$

Where $\otimes$ means convolution, $\hat{r}(n)$ is reconstructing signal, $h(n)$ is the impact response of the reconstruction filter.

The useful signal after the digital SIC is given by:

$$x(n) = r(n) - \hat{r}(n) \tag{10}$$

Next, the LMS adaptive algorithm real-time adjust the filter weight vector $\mathbf{H}$, and take the useful signal $x(n)$ from (10) as the error signal to achieve the best requirements of signal in output system. The cost function is given by:

$$J = E\left(\|x(n)\|^2\right) = E\left(\|r(n) - \hat{r}(n)\|^2\right) \tag{11}$$

Considering the practical application, the instantaneous gradient method used in the LMS adaptive algorithm:

$$\hat{\nabla}\left(\|x(n)\|^2\right) = 2x^*(n)\hat{\nabla}\left(x(n)\right) = -2s(n)x^*(n) \tag{12}$$

Where $x^*(n)$ is the conjugation of $x(n)$.

Then, we can obtain weight updating expression of the algorithm.

$$H(n+1) = H(n) - \mu s(n) x^*(n) \tag{13}$$

Where, μ is the step factor of convergence, $H(n)$ and $H(n+1)$ are the filter weight vector of n and $n+1$ moment respectively.

IV. NUMERICAL ANALYSIS

As shown in figure 1, the full-duplex system simulation system is based on MATLAB, verifed the feasibility of the proposed algorithm. The main simulation parameters are listed in Table 1:

TABLE I. SIMULATION PARAMETERS OF SMALL CELL

Parameters	Values	
System Frequency	2.4GHz	
Signal bandwidth	10MHz	
Desired signal power	-68dBm	
noise	-98dBm	
Antenna distance between transmitter and receiver	20cm	
channel model	Before RF SIC	Rician (lower KL)
	After RF SIC	single path Rayleigh fading

In this paper, we present an a digital SIC algorithm based on spectral estimation, and we simulat the proposed algorithm and compared it with the adaptive channel estimation algorithm based on training sequence.

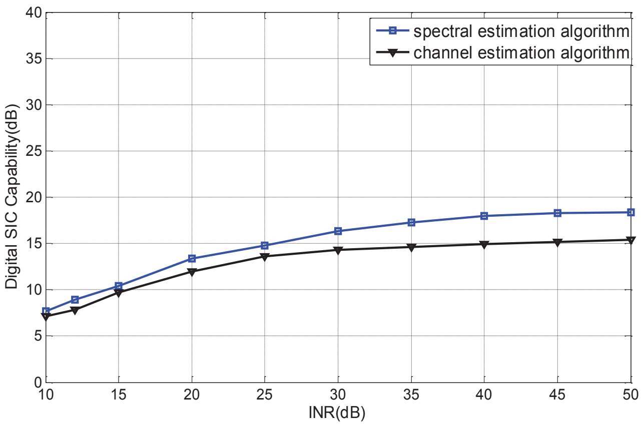

Fig.2 the ability of digital SIC

From Fig. 2 we can observe that the ability of digital SIC of two kinds of SCI algorithms which are spectral estimation algorithm and channel estimation algorithm, respectively. The ability of digital SIC are improved with the increasing of the interference signal power. The proposed algorithm has been reconstructed the phase recovery, and the eliminate performance is improved by 3dB compared with the adaptive channel estimation algorithm.

V. CONCLUSION

Full-duplex wireless communication technology has significant advantages in improving the spectrum efficiency, data throughput, wireless access with collision avoidance and reducing congestion and so on. We present a digital SIC algorithm based on spectral estimation via analyze the spectrum of the SIS and digital transmitting signal, then reconstruct and eliminate SIS via the second-order cyclic statistics information of signals. The algorithm improves the performance of digital SIC, and has better convergence and lower computational complexity compared channel estimation algorithm. Next step, we will explore and research on the best combination of analog and digital self-interference elimination.

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