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Self-interference Cancellation in Co-time and Co-frequency Full Duplex System

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***Abstract*-It is of particular importance to use the limited spectrum resources efficiently since they are non-renewable. The spectrum efficiency can be doubled theoretically with the Co-time Co-frequency Full Duplex (CCFD) technology. Existing research results show that CCFD is achievable under the condition of enough amount of self-interference cancellation. In this paper, we propose a self-interference cancellation method with which antenna separation is combined with analog self-interference cancellation and digital self-interference cancellation. The simulation results show that performance of self-interference cancellation is greatly improved and the interference cancellation ratio (ICR) is nearly 110dB with the proposed method.**

Keywords-co-time and co-frequency full duplex (ccfd); self-interference cancellation; adaptive digital cancellation

I. INTRODUCTION

With the fast development of mobile communication services and the emergence of new types of applications, wireless spectrum resources would be rarer and rarer. So, it is of particular importance to use the limited spectrum resources efficiently. Traditional duplex modes include frequency division duplex (FDD) and time division duplex (TDD) by which signals are transmitted and received by using different frequency bands and different time slots, respectively. Therefore, the interference on the frequency domain and time domain of transmitting signal to receiving signal can be avoided. While, the resource costs are doubled in duplex communication systems using either FDD or TDD [1].

Fortunately, Co-time and Co-frequency Full Duplex (CCFD) is a technique by which signals can be transmitted and received in the same frequency band simultaneously. It is a new breakthrough to enhance spectrum utilization by doubling spectrum efficiency theoretically. The fifth generation (5G) mobile communication technology is a new generation of mobile communication system developing for communication demand after 2020. Transmission speed and resource utilization need to be improved in 5G [2]. As a result, CCFD has become a potential technology and popular research topic in 5G mobile communication system.

Generally, the local receiving antenna could receive not only desired signals from remote node, but also signals from local transmitting antenna, Since the distance between transmitting antenna and receiving antenna in the same node is much shorter than the distance between remote transmitting antenna and local receiving antenna, so the power of the interference signal received from local transmitting antenna would be much larger than the power of the desired signal from remote node. In order to implement CCFD, the primary problem is to obtain desired signal with smaller power from received signal containing high power self-interference signal. Self-interference cancellation is just a technology to solve such a problem.

In [3] the authors proposed an analog self-interference cancellation scheme based on gradient descent. In [4] a RF cancellation of direct coupling was proposed. A scheme was given in [5] with which the signal coupled from transmit chain is converted into digital domain and then will be cancelled in digital domain. While, in this scheme the problem of the quantification performance of analog-to-digital converter (ADC) for large or small signal cannot be taken into account. Thus, desired signals might be lost in the quantization. Further research on effective algorithm of digital self-interference cancellation can be found in [6,7,8].

Currently, most researchers focused on analog domain or digital domain self-interference cancellation separately. They've seldom discussed the system as a whole. In fact, cancellation of analog domain might influence the further cancellation of digital domain. In this paper, we propose a method by which antenna separation is combined with analog self-interference cancellation and digital self-interference cancellation in order to implement CCFD. Then main ideas of this method are as follows: (1) directly coupling is applied in analog self-interference cancellation; (2) in digital self-interference cancellation digital baseband signal and adaptive filter are used to remove the cancellation signal generated by adaptively adjusting the filter coefficients from the received signal. Let N denote the order of the analog domain filter and T denote the radio of the main delay of the self-interference to sampling period. Existing analysis and simulation results show that by using analog self-interference cancellation the larger N is, the higher the value of self-interference cancellation is, when N is between about T and twice of T. While, the value of self-interference cancellation would decrease as N increases when N is greater than twice of T. The self-interference cancellation amount of approximately 110dB could be obtained by combining of antenna separation, appropriate analog self-interference cancellation with digital self-interference cancellation.

The paper is organized follows: in Section Ⅱ the model of the self-interference cancellation system is given; the self-interference cancellation system is analyzed in section III;

the simulation results are shown in Section Ⅳ; Section Ⅴ is a conclusion of this paper.

II. THE MODEL OF THE SELF-INTERFERENCE CANCELLATION SYSTEM

We will take the local transceiver as an example to introduce the implementation of the self-interference cancellation system since the structures of the local and the remote transceiver are identical. Digital transmitting signal generated randomly would be transmitted out by transmitting antenna after going through binary phase shift keying (BPSK), pulse shaping filter, digital-to-analog conversion (DAC) and frequency up-conversion. The signals received by the receiving antenna include both the desired signal from the remote transmitter and the interference signal from the local transmitter. First of all, the received signal is processed by analog self-interference cancellation circuit, then by the digital self-interference cancellation after down-conversion and DAC, furthermore passed through a matched filter. An estimated value of the desired signal is obtained after demodulation the residual signal. The block diagram of the self-interference cancellation system proposed in this paper is shown in Fig. 1. The local signal parameter is represented by the subscript l and the remote signal parameter is represented by the subscript f .

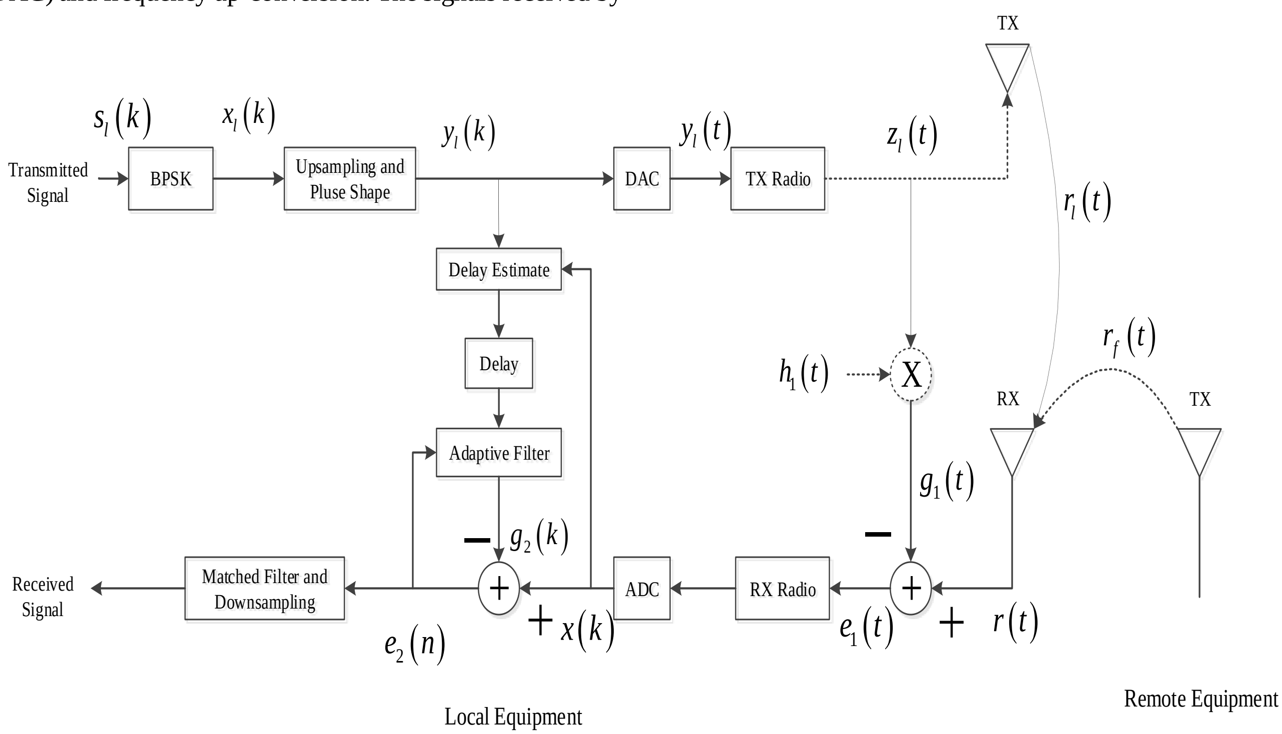

Figure 1. The block diagram of the self-interference cancellation system.

A. Transmit Chain

Let the randomly generated local transmitting signal $s_l(k)\in\{0,1\}$ denote the k-th transmitting digital signal. The sequence $x_l(k)\in\{-1,1\}$ is obtained after BPSK modulation, where 0 corresponds to -1 and 1 corresponds to 1. The output sequence $y_l(k)$ will be obtained after the digital baseband signal goes through pulse shaping filter (square-root raised cosine):

$$y_l(k)=x_l(k)\otimes h(k) \tag{1}$$

where $h(k)$ is the square-root raised cosine pulse function.

$y_l(k)$ is converted into an analog signal $y_l(t)$, which could be transmitted out by transmitting antenna after being up-converted to the transmit frequency, via DAC. The local transmitting signal is:

$$z_l(t)=\sqrt{50\times P_l}\,y_l(t)\cos(2\pi f_c t+\varphi_l) \tag{2}$$

where P_l is the power of the local transmitting signal with Watt(W) as the unit and φ_l is the initial phase of the local carrier.

Similarly, like the local transmitter, the signal from the remote transmitter can be given as follows:

$$z_f(t) = \sqrt{50 \times P_f}\, y_f(t) \cos(2\pi f_c t + \varphi_f) \quad (3)$$

where $y_f(t)$ is obtained after $y_f(k)$ is converted through DAC, $y_f(k)$ is:

$$y_f(k) = x_f(k) \otimes h(k) \quad (4)$$

P_f is the power of the remote transmitting signal and φ_f is the initial phase of the remote carrier.

B. Channel Model

Assuming that the signal propagates between local transceivers over Additive White Gaussian Noise (AWGN) channel, then k_l and t_l will be amplitude attenuation and delay respectively. Similarly, assuming that the remote transmitting antenna goes through AWGN channel when it reaches the local receiving antenna, then the amplitude attenuation and the delay would be k_f and t_f respectively. The local received signal $r(t)$ is composed of desired signal $r_f(t)$ from the remote transmitter, self-interference signal $r_l(t)$ from the local transmitter and the Gaussian white noise $n(t)$.

$$\begin{aligned} r(t) &= r_f(t) + r_l(t) + n(t) \\ &= k_f z_f(t - t_f) + k_l z_l(t - t_l) + n(t) \end{aligned} \quad (5)$$

Let l_f be the distance between the remote transmitting antenna and local receiving antenna, l_l be the distance between local transmitting and receiving antennas; $c = 3 \times 10^8 \, m/s$ is the propagation velocity of the electromagnetic wave. We have:

$$t_f = \frac{l_f}{c}, t_l = \frac{l_l}{c} \quad (6)$$

C. Receive Chain

The estimated self-interference signal $g_1(t)$ in analog domain is used to perform analog self-interference cancellation.

$$g_1(t) = z_l(t) \otimes h_1(t) \quad (7)$$

$$e_1(t) = r(t) - g_1(t) = r_f(t) + r_l{}'(t) + n(t) \quad (8)$$

Where $h_1(t)$ is the impulse response of analog self-interference cancellation circuit and $r_l{}'(t)$ is the residual self-interference signal.

The residual signal, $e_1(t)$, will be down-converted and an oscillator which is the same as up-conversion will be utilized. The down-converted signal which consists of analog baseband signal and high-frequency signal with frequency $2f_c$ is filtered by a low-pass filter with cut-off frequency greater than the frequency of the analog baseband signal. Then, digital baseband signal $x(k)$ will be obtained when the filtered signal goes through ADC:

$$x(k) = r_f(k) + r_l{}'(k) + n(k) \quad (9)$$

The signal removing the interference, $e_2(k)$, will be obtained after digital self-interference cancellation using reconstructed self-interference signal in digital domain $g_2(k)$, which given as:

$$g_2(k) = y_l(k) \otimes h_2(k) \quad (10)$$

$$e_2(k) = x(k) - g_2(k) = r_f(k) + r_l{}'(k) - g_2(k) \quad (11)$$

Where the transfer process of the signal from $y_l(k)$ to $g_2(k)$ is considered as a channel, and $h_2(k)$ is the estimated time-domain response of the channel.

Residual signal $e_2(k)$ can be demodulated after passing through matched filter which is the same as the one in the transmitter. Then an estimated value of the remote transmitting signal can be obtained.

III. THE ANALYSIS OF THE SELF-INTERFERENCE CANCELLATION SYSTEM

A. Antenna Interference Cancellation

Antenna interference cancellation is negative interference cancellation. The amount of interference cancellation is related to the placement, radiation pattern and the distance between transmitting and receiving antennas. In the free-space path loss model, power loss is directly proportional to the square of distance between transmitting and receiving antennas and inversely proportional to the square of transmitting signal frequency. It can be expressed as follows:

$$P_L = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) \qquad (12)$$

Where P_L is path loss with dB as its unit, d is the distance between the transmitting and receiving antennas with m as its unit and λ is the wavelength of the transmitting signal with m as its unit.

Attenuation amount of the self-interference signal in radio channel can be increased by increasing the distance between the transmitting and receiving antennas or changing radiation pattern. However, by antenna interference cancellation only the self-interference signal cannot be removed completely. In fact, the distance between local transmitting and receiving antennas is usually very close, so the amount of interference cancellation is very limited.

B. Analog Self-Interference Cancellation

The analog self-interference cancellation includes direct coupling and indirect coupling, where indirect coupling means adding a wired link that a generated radio frequency (RF) signal which has the same channel fading as the original signal is subtracted from the received signal; direct coupling means the coupled RF signal from transmitting antenna is attenuated and delayed, then transmitted to receiver in which self-interference cancellation is done. In this paper we use the cancellation of direct coupling, i.e. a multi-order analog filter is applied to adjust amplitude and delay of RF signal from transmitting antenna, after which $g_1(t)$, an estimated value of self-interference signal, can be obtained. Then, $g_1(t)$ is subtracted from the received signal and analog self-interference cancellation is completed.

After the analog self-interference cancellation, the received signal is converted to the digital domain by ADC. The quantification performance of ADC to a big signal is different from that to a small signal (when the received signals have different amplitudes). According to theoretical analysis in [9], the range of the received signal is $[a,b]$ and when the quantization bit is L, the values of the number of quantization interval $M = 2^L$, the quantization interval $\Delta V = \frac{b-a}{M}$ and quantization noise $N_q = \frac{\Delta V^2}{12}$ are determined. Generally, theoretical value of quantization signal-to-noise ratio (SNR) is:

$$SNR = \frac{X}{N_q} = 6L + 1.76 + 20\lg x, x \in [0,1] \qquad (13)$$

Where x is normalized signal and X is the power of x. Quantization SNRs of big signal and small signal are different, and quantization SNR of small signal is relatively weak, even small signal is covered in quantization noise.

Theoretical value of the dynamic range of ADC is:

$$DR(dB) = 6.02L + 1.76(dB) \qquad (14)$$

For example, a 10-bit ADC, the dynamic range of which is more than 60dB, while the power difference between the self-interference signal and the desired signal is much higher than 60dB. The higher the bit of ADC is, the higher the cost will be. The bit of ADC is limited, and it is not a good idea to increase the bit of ADC. Therefore, the self-interference signal must be reduced to a certain level before ADC. From the above analysis, the analog self-interference cancellation is a crucial step in the self-interference cancellation system.

C. Digital Self-Interference Cancellation

The digital self-interference cancellation utilizes adaptive interference cancellation method based on digital adaptive filter. A replica of self-interference signal is generated via adjusting the coefficients of the adaptive filter and then is subtracted by the received signal. Digital domain cancellation module consists of a delay estimation unit to estimate the delay between local transmitting digital signal and self-interference signal, a variable delay unit to compensate for the time delay and an adaptive filter unit to track signal. The input signal of the module is the local transmitting baseband signal $y_l(k)$ and the received signal $x(k)$. Firstly, A time delay is compensated for $y_l(k)$, and then $g_2(k)$, reconstructed interference signal, is obtained via adjusting the coefficients of adaptive filter; finally, the reconstructed interference signal is subtracted from the received signal. The output signal $e_2(k)$ provides a feedback to adaptive module and the filter coefficients are adjusted accordingly. The estimated value of the desired signal can be gotten via demodulation after the output signal converges.

Typical adative algorithms includes least square etimation, minimum mean square error, steepest-descent algorithm. Here, we adopt a widely used algorithm, the least mean square algorithm (LMS). The principle of LMS will not be described here, and only the rationality of the algorithm will be discussed. The residual self-interference signal has the same source with the reconstructed interference signal and they are correlated each other, while the residual self-interference signal is irrelevant to the desired signal from the remote expected one. So the value of term, $E\left[2r_f(k)\left(r_l'(k)-g_2(k)\right)\right]$, in Eq. 15 is zero. The desired signal power will not be affected when the coefficients of the adaptive filter is adjusted to minimize $E\left[e_2(k)\right]$.

$$\begin{aligned} E\left[e_2(k)\right] &= E\left[r_f^2(k)\right] + E\left[\left(r_l'(k)-g_2(k)\right)^2\right] \\ &+ E\left[2r_f(k)\left(r_l'(k)-g_2(k)\right)\right] \\ &= E\left[r_f^2(k)\right] + E\left[\left(r_l'(k)-g_2(k)\right)^2\right]. \end{aligned} \tag{15}$$

The digital self-interference cancellation can be realized when the filter coefficients converge to the optimum values. In order to achieve a better digital domain cancellation performance, the training sequence is sent firstly and used to estimate $h_2(k)$ by which is the initial filter coefficients are set. The change of the channel will be tracked precisely by adaptive algorithm. The differences between the filter output and the desired signal will become smaller by adjusting the coefficients of the filter according to the output signal $e_2(k)$.

IV. SIMULATION RESULTS

Based on MATLAB platform, simulation analysis has been discussed for the self-interference cancellation model proposed in this paper. Interference cancellation ratio (ICR) of the simulation results refers to ratio of signal power before interference cancellation to the one after interference cancellation. Since ICR is irrelevant to signal modulation type, BPSK modulation, a relatively simple one will be used in this paper. Simulation parameters are shown in Table 1.

The distance between the transmitting antenna and receiving antenna in a same node is close, so a reasonable hypothesis can be made here: the distance between the transmitting antenna and receiving antenna in a same node is 20cm. According to the path loss model mentioned before, attenuation with 26dB will be happened at 2.4GHz. The analog domain uses multi-order filter to reconstruct the self-interference signal and the order of filter has a dramatically impact on the performance of analog self-interference cancellation. According to Eq. 6, t_l is $6.67e-10s$. The sampling frequency f_s is set to 10GHz and the sampling period T_s is $10^{-10}s$. So T, the ratio of the main path delay of the self-interference to sampling period, is:

$$T = \frac{t_l}{T_s} \approx 7 \tag{16}$$

TABLE I. SIMULATION PARAMETERS

Modulation	BPSK
Roll-off factor	0.25
Signal bandwidth	5[MHz]
System frequency	2.4[GHz]
Self-interference signal power	0[dBm]
Desired signal power	-80[dBm]
Channel model	AWGN
SNR	35[dB]

The variation of ICR in analog domain with analog domain filter order is shown in Fig. 2. According to the Fig. 2, the value of self-interference cancellation would increase as N, the order of analog domain filter, increases when N is between about T and twice of T which is the ratio of the main path delay of the self-interference to sampling period; the value of self-interference cancellation would decrease as N increases when N is greater than about twice of T.

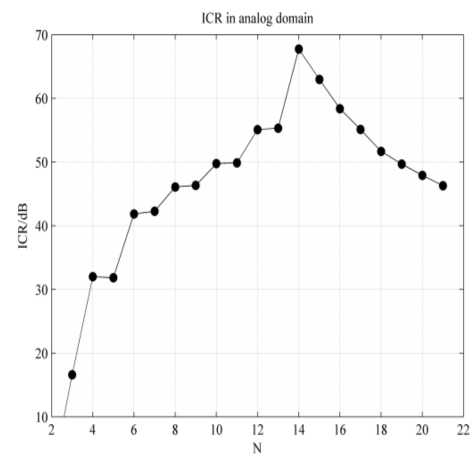

Figure 2. ICR in analog domain.

After the analog self-interference cancellation, further cancellation works as it is converted into digital domain through ADC. In Fig. 3 the variation of ICR in digital domain with analog domain filter order is shown when the digital domain filter order is 16. As can be seen from Fig. 3, when N, the analog domain filter order, lies between around T and 2T, the digital self-interference cancellation will have a relatively better performance and the optical ICR in digital domain would be in the vicinity of 16dB.

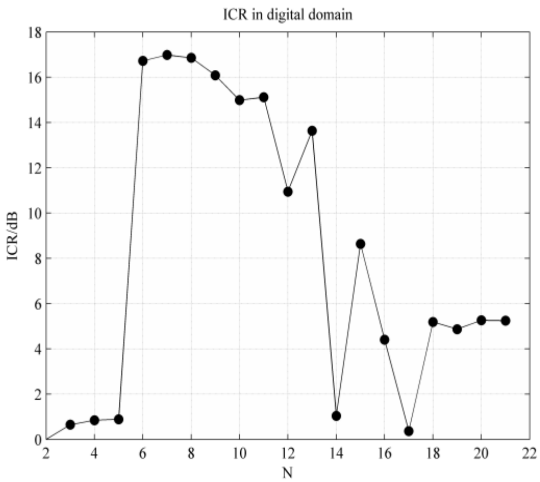

Figure 3. ICR in digital domain.

The variation of ICR in the whole system with analog domain filter order is shown in Fig. 4. ICR in the whole system is the radio of local transmitting signal power to the power of the signal after antenna separation, analog self-interference cancellation and digital self-interference cancellation. The order of digital domain filter is 16. As can be shown in Fig. 4, when N is approximately greater than T, the system can get a better ICR which can be even greater than 110dB.

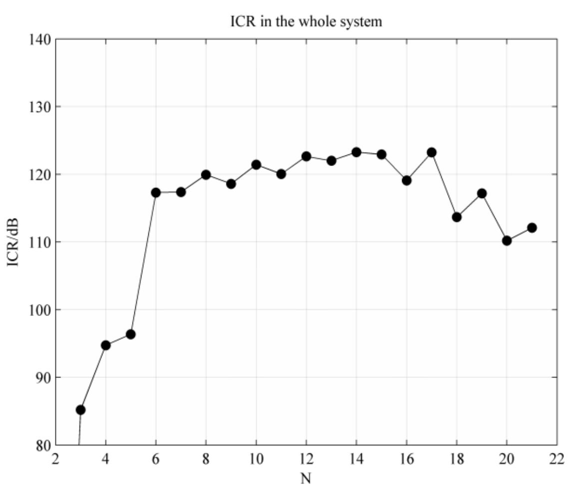

Figure 4. ICR in the whole system.

V. CONCLUSION

In this paper, we propose a self-interference cancellation method in which that antenna separation, analog self-interference cancellation and digital self-interference cancellation are combined. Simulation of the whole system has also been done. In the analog domain, direct coupling is used to reconstruct the interference signal; in the digital domain, adaptive filter is used to generate a copy of the interference signal. Simulation results show that with antenna separation, appropriate cancellation in analog domain and digital domain combined, ICR in the whole system can achieve about 110dB.

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