Digital Interference Cancellation in Single Channel, Full Duplex Wireless Communication

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***Abstract*—This paper describes a single channel, full-duplex wireless communication system that can receive and transmit at the same frequency band in the same time. Recent researches have proved the feasibility of full duplex wireless communication in practice, by canceling the self-interference signal to obtain the desired signal. In this paper, we propose an adaptive digital self-interference cancellation technique, which combines with existing antenna separation and balun based cancellation to achieve the quantity of self-interference cancellation needed for full-duplex system. An adaptive filter based on least mean square (LMS) algorithm is applied to track amplitude and phase variations to produce an expected cancellation signal, after the initial delay and frequency offsets are compensated. Our simulation results display that the adaptive digital interference cancellation scheme has fairly desirable self-interference signal cancellation performance.**

Keywords-full duplex single channel system;self-interference cancellation;adaptive digital cancellation;LMS algorithm

I. INTRODUCTION

Efficient use of the limited available wireless spectrum resource is a key target of wireless communication systems. In conventional wireless communication systems, the two main processes for preventing interference are time-division and frequency-division, which separate the uplink and downlink channels in the time domain and frequency domain to achieve bidirectional communication, both approaches are so-called half-duplex communication techniques. In this paper, we will discuss a technique to transmit and receive signals in the same frequency band simultaneously. Comparing with traditional methods, single channel in place of two ones is used for duplex, thus in theory, channel capacity can potentially be twofold comparing with half-duplex.

The full-duplex communication causes wide attention, although it has been proposed in a short while, and it sounds a little extraordinary. Some recent researches have verified the feasibility of full duplex wireless device in practice [1-6]. To realize full duplex operation, the key issue is that how to as much as possible cancel the large self-interference signal. One approach to analog cancellation employs a second transmitting wire to produce an analog cancellation signal, which is subtracted from the received signal. Some analog interference cancellation mechanisms use QHx220 noise canceling chip to remove a known analog self-interference signal from the received signal. In [1], antenna cancellation is proposed, as a novel technique, by combining with analog and digital cancellation to remove the interference signal, Choi et al. evaluate the performance of 802.15.4 full duplex prototype, which is close to an ideal full duplex system. In [2, 3], some experimental results and data-driven analysis on narrow band self-interference cancellation using antenna separation, analog interference cancellation and digital cancellation are presented, and prove the single channel full-duplex system is feasible. Nevertheless, recently most researches concentrate on antenna placement and analog interference cancellation, the study of digital interference cancellation is only a few in [1, 2, 3, 4], and the performance is not very desirable. For example, the digital interference cancellation achieves only around 10dB reduction of self-interference signal in [1].

In this paper, we propose an adaptive digital interference cancellation based on adaptive filter, which combines with antenna separation and analog cancellation, to achieve full-duplex communication. The basic idea of our technique is to estimate the required parameters, which are applied to samples of the known transmitted signal to produce a cancellation signal corresponding to the self-interference signal. Since the channel is time varying, we use the adaptive filter to adjust automatically parameters to produce an expected cancellation signal, then this signal is subtracted from the received signal. Through analysis and simulation results, we can prove this technique is suitable for self-interference cancellation, and can remove approximately 20dB of self-interference. The detailed description of the adaptive digital interference cancellation is in Section II. In Section III, simulation results of this paper are shown. At the last, the cancellation method is summarized and conclusion is presented in Section IV.

II. ADAPTIVE DIGITAL INTERFERENCE CANCELLATION SYSTEM ANALYSIS

A. Key Challenge in Achieving Full-duplex System

The objective of a single channel full duplex system is to transmit and receive simultaneously at the same frequency band. The key problem of full-duplex technique is that a node receives not only the signal which it wants to receive, but also the signal which is transmitting by its own transmit antenna, i.e. self-interference signal, which is hundreds of thousands of times stronger than the desired received signal from other nodes. We must cancel the large self-interference signal from the received signal to ensure that a full duplex node can extract the desired received signal.

Recently, most systems process signal in digital domain, the analog signal can be converted to the digital signal through an analog-to-digital converter (ADC). The ADC's dynamic range at the receiver is the maximum radio between the strongest and weakest received signal power. Once the dynamic range is overtopped, the quantization noise of the ADC can overwhelm the weakest signals. The dynamic range of the ADC can be computed by the following formula:

$$\mathrm{DR}(\mathrm{dB}) = 6.02 \times n + 1.76\,\mathrm{dB}, \qquad (1)$$

where n is the number of bits in the ADC resolution. However, in full-duplex wireless system, the self-interference signal is stronger (60-70dB) than the desired received signal. And the dynamic range of existing ADC isn't large enough to capture the desired received signal in the situation that exists such large self-interference, so that the desired received signal is lost in quantization process. Hence, the demand for antenna placement and analog self-interference cancellation before digital interference cancellation becomes quite obvious. In our paper, we would like to combine antenna separation [2] with balun cancellation [4] to achieve sufficiently self-interference cancellation before the received signal arrives at the ADC. After that we use the adaptive digital interference cancellation proposed by us to further cancel self-interference in digital domain.

First, a brief introduction about antenna separation and balun based cancellation is described. Antenna separation is a passive mechanism by separating the transmit and receive antennas in the same node as much as possible physical distance, which makes use of the attenuation due to path loss between the two antennas. A simplified free-space path loss is calculated as follow:

$$\mathrm{PathLoss}(\mathrm{dB}) = 32.44 + 20\log_{10}(f) + 20\log_{10}(d), \qquad (2)$$

where f is the carrier frequency in MHz and d is the distance in km.

Balun cancellation is proposed by Choi et al. [4], using a balanced-to-unbalanced converter (balun) in an absolutely new way. This approach obtains the inverse of a self-interference signal by a balun and uses this generated inverted signal to cancel the self-interference signal. The transmit antenna of a node transmits the positive signal which produces the self-interference signal. For canceling the self-interference signal, the radio combines the negative signal from the balun with its received signal. The inverse signal is a modified signal by a variable delay element and a variable attenuator to as far as possible match the self-interference signal. The balun based cancellation technique theoretically has no limitation on bandwidth or power, and can cancel the self-interference signal perfectly, at least 45dB.

We consider a basic system configuration with two nodes, which attempt to transmit and receive a signal simultaneously at the same frequency band, each node has only one transmit

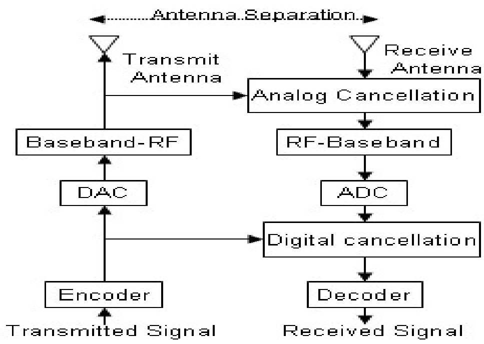

Figure 1. Simple block diagram of a wireless full-duplex node

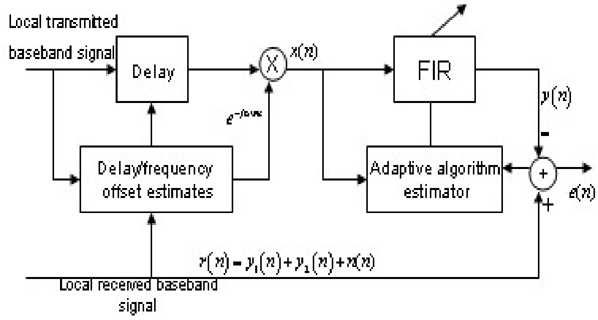

Figure 2. Block diagram of adaptive digital interference cancellation

antenna and one receive antenna. Since the structure is symmetric, we can only take into account one node, a simple cancellation block diagram of a wireless full-duplex node is shown in Fig.1. Assuming the distance between the transmit and receive antenna in the same node is 20cm, in this way, antenna separation and balun cancellation can remove nearly 71dB self-interference, that is sufficient to make the weak received signal pass through ADC within the dynamic range. Then, the remaining self-interference signal can be cancelled in digital domain.

B. Adaptive Digital Interference Cancellation

The adaptive self-interference cancellation system (ASIC) based on digital adaptive filter is shown in Fig.2, which is proposed as a solution to remove the self-interference signal samples from the residual hybrid received signal in digital domain. The task of the cancellation block is to create a resembled replica of the interference signal and subtract it from the received signal by adaptively adjusting filter's parameters. The signal from the transmitter is measured as late as possible in the transmitter, normally just before the DAC, to avoid as many imperfections as possible. The system contains: a variable delay element to compensate for the time delay, a delay/frequency estimation unit which is used for estimating the initial delay and frequency offset between the local transmitted signal and the self-interference signal, by employing a known ambiguity processing algorithm in [7], and an adaptive filter tracking variation parameters, that is used for samples of the known transmit signal to emerge the desired cancellation signal which is subtracted from the composite received signal. To be able to perform aforesaid estimation, a reference signal is needed. Referring to the Fig.2, the primary

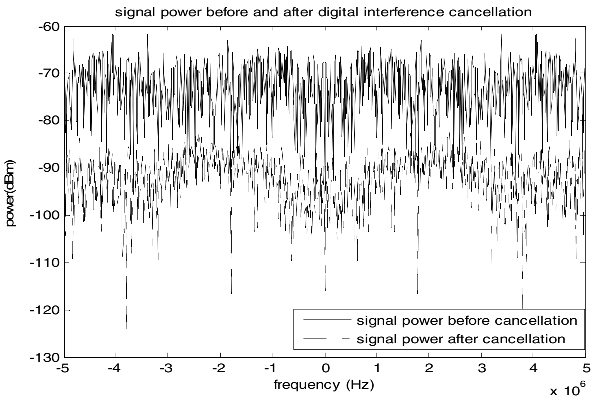

Figure 3. Signal power before and after adaptive digital cancellation

input picks up the received signal after antenna separation and balun cancellation, the received signal is:

$$r(n) = y_1(n) + y_2(n) + n(n), \quad (3)$$

where $y_2(n)$ is the desired received signal, $n(n)$ is random additive noise, $y_1(n)$ is the remaining self-interference signal. The reference input only consists of a reconfiguring signal $x(n)$ that is a coarse replica of the self-interference signal by compensating the delay and frequency offset to the known transmitted signal. The self-interference signal and the reconfiguring signal have a common signal source; hence they are correlated with each other, but are uncorrelated with the desired received signal. The reconfiguring signal passes through an adaptive FIR filter, whose output signal $y(n)$ is a minimum mean square estimate of the self-interference signal in primary input. This self-interference signal estimate is subtracted from the corrupted received signal in primary input, to produce an estimate of the desired received signal as the ASIC system output $\hat{y}_2(n)$. In such system, a practical objective is to produce a system output that is the best fit in the least squares sense to the desired signal. This goal is completed by feeding the ASIC system output $\hat{y}_2(n)$ back to the adaptive filter and adjusting the filter coefficients through an adaptive algorithm to minimize total system output power. In other words, the cancellation system output $\hat{y}_2(n)$ acts as the error signal for the adaptive process, the output of the filter as follow:

$$\hat{y}_2(n) = y_1(n) + y_2(n) - y(n). \quad (4)$$

Taking expectation of both sides of the above relationship:

$$\begin{aligned} E\left[\hat{y}_2(n)\right] &= E\left[y_2^2(n)\right] + E\left[\left(y_1(n) - y(n)\right)^2\right] \\ &+ E\left[2y_2(n)\left(y_1(n) - y(n)\right)\right] \\ &= E\left[y_2^2(n)\right] + E\left[\left(y_1(n) - y(n)\right)^2\right] \end{aligned}. \quad (5)$$

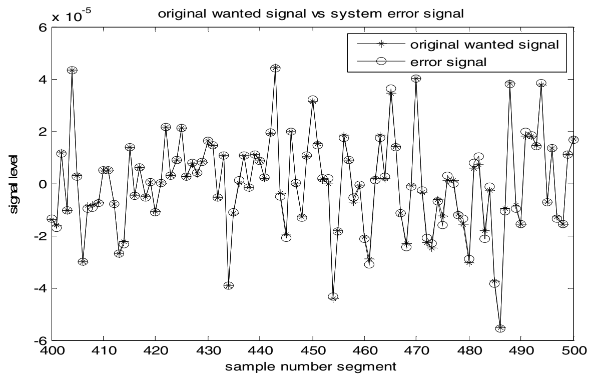

Figure 4. Cancelled waveform with the desired signal waveform.

Because the signal power $E\left[y_2^2(n)\right]$ is unaffected when the adaptive filter is adjusted to minimize $E\left[\hat{y}_2(n)\right]$. Namely:

$$\min E\left[\hat{y}_2(n)\right] = E\left[y_2^2(n)\right] + \min E\left[\left(y_1(n) - y(n)\right)^2\right]. \quad (6)$$

When the filter converges to the optimal coefficients, this system can realize self-interference cancellation. This is equivalent to transforming the output $\hat{y}_2(n)$ to be a best least squares estimate of $y_2(n)$, the mean error of the adaptive self-interference cancellation system in our paper is expressed as:

$$\mathrm{P} = E\left\{\left[\hat{y}_2(n) - y_2(n)\right]^2\right\}. \quad (7)$$

Note that the desired received signal from the primary input can not leak in the reference signal; otherwise, the desired received signal will be offset.

In our paper, the self-interference cancellation technique is based on an adaptive Least Mean Square (LMS) algorithm. The LMS algorithm is widely used for adaptive filtering. For simplicity, we don't recommend in detail about the derivation process of the LMS algorithm. In our paper, we only give the realize formula of the algorithm, we use $h(n)$ to denote the weight of the filter, μ denotes a step side and $e(n)$ denotes the filter error. As follows:

$$\begin{aligned} & y(n) = x^T(n)h(n) \\ & e(n) = \hat{y}_2(n) = y_1(n) + y_2(n) - y(n). \\ & h(n+1) = h(n) + 2\mu x(n)e(n) \end{aligned} \quad (8)$$

III. Simulation Results

In this section we provide simulation results for our system. The transmit power is 0dBm. Note that the two nodes are fixed, and the transmit antenna is very close to the receive antenna located in the same node, the channel between them will be fairly stabilize, and the effect of fading is almost time-invariant within the period of a packet time, we can model the channel using adaptive FIR filter. Herein, we consider a simple uniform propagation pattern, as mentioned earlier, the reasonable distance between the transmit and receive antennas used for antenna separation is about 20cm, which results in path loss of about 26dB for 2.4GHz, and we assume the noise

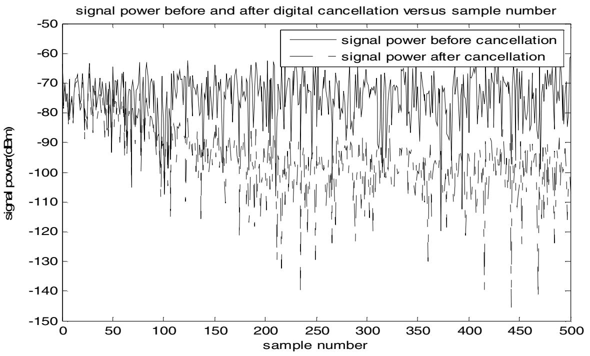

Figure 5. Signal power before and after digital interference cancellation versus sample number when μ =0.01.

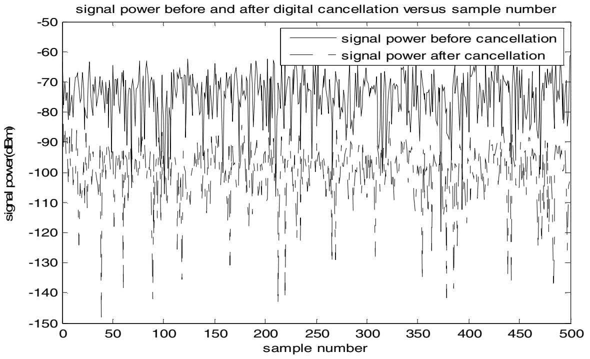

Figure 6. Signal power before and after digital interference cancellation versus sample number when μ =0.099.

floor is approximately -90dBm, hence, we need to cancel nearly 90dB of self-interference signal to extract the desired received signal, and ensure the reception don't be disrupted by its own transmission. The balun cancellation in [3] can cancel at least 45dB of self-interference, therefore, after antenna separation and balun based cancellation, the residual self-interference is about -71dBm.

We analyze the reduction of the self-interference signal by observing the self-interference signal power before and after using adaptive digital interference cancellation. Fig.3 shows the signal power before and after adaptive digital cancellation, the solid line denotes the power before cancellation, the dotted line represents signal power after passing through adaptive digital interference cancellation system, it demonstrates that our cancellation method has the capability of canceling about 20dB self-interference signal, which is superior to the digital cancellation in [1], around 10dB.

We also compare the desired received signal waveform with the resulting signal waveform after cancellation as Fig.4 shown, that indicates the adaptive digital interference filter could eliminate the impact of self-interference signal after compensating the delay and frequency offset, and its output is better to remain the desired signal waveform. In addition, we investigate the influence of LMS adaptive algorithm's step factor on adaptive digital self-interference cancellation. We look into signal power versus sample number before and after adaptive digital self-interference cancellation. Fig.5 and Fig.6 plot signal power versus sample number, simulations are performed for different step factor, μ =0.01 and μ =0.099 respectively. We can obtain that algorithm convergence rate will become quicker in the increase of the step factor, and the cancellation performance can keep basically consistent after convergence. In the meantime, we also see the convergence rate of LMS adaptive algorithm through the above figure, in addition to the initial stage, the convergence rate is very fast. These simulation results testify the effectiveness of our adaptive LMS, which is used as a preferred algorithm for adaptive digital interference cancellation with fairly good performance, robustness.

IV. CONCLUSIONS

In this paper we propose a new technique for wireless systems that allows two nodes to transmit and receive signals in the same channel at the same time. An adaptive digital interference cancellation method based on adaptive filter is proposed. The adaptive filter can track the real-time changes of the self-interference signal and adaptively adjust own coefficients with the error signal to minimize fine delay, amplitude and phase offsets between the self-interference signal and the recreated signal.

Simulation results have shown that this method is possible to cancel about 20dB of self-interference signal, combining with antenna separation and balun based cancellation; they can eliminate enough self-interference signals to achieve full-duplex wireless communication. A significant characteristic of the LMS algorithm is simplicity, and the algorithm provides both sufficient convergence rate and low maladjustment. Due to its low calculative cost, this algorithm is a good choice to implement in hardware.

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