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***Abstract*—Self-Interference has been significantly reduced by current cancelation methods for the practical design of Full-Duplex wireless. However, the residual self-interference is still much stronger than the thermal noise due to many factors, e.g. phase noise in local oscillator, I/Q imbalance, thermal noise and so on, limiting the self-interference cancelation. In this paper, the influence of the thermal noise on the active self-interference cancelation (ASIC) for wideband Full-Duplex OFDM wireless system is analytically studied and demonstrated. We propose a little modification to the structure of data packet of IEEE 802.11g to reduce the impact of the thermal noise on the active self-interference cancelation (ASIC) for Full-Duplex OFDM wireless. The ADS-Matlab co-simulation results show that we can reduce the residual self-interference to only 1.5dB higher than the receiver thermal noise.**

Keywords*—*Full-Duplex; OFDM; Self-interference; Radio

I. Introduction

Conventional radio devices work on the Half-Duplex mode (e.g. FDD, TDD), employing orthogonal radio resource for transmitting and receiving, to avoid the strong co-channel self-interference generated from the same radio node. This paper studies the Full-Duplex mode where the radio device can transmit and receive signals on the same frequency at the same time. One of the advantages of this technology is that it potentially doubles the throughput of current wireless link. Besides, it also can be applied to the cognitive radio network and relay network where Full-Duplex can provide significant advances.

Current research results [1] have demonstrated that short-range Full-Duplex wireless communications is feasible by combining passive suppression and active cancelation of the self-interference. Although the self-interference has been significantly reduced, the residual self-interference after suppression and cancelation is still so strong that Full-Duplex is hard to be put into practice. With respect to the research of ASIC for Full-Duplex wireless, the work [2] investigates the hardware issues, including transmit quantization, transmit noise, transmit nonlinearities, transmit in-phase and quadrature (IQ) imbalance, receive quantization, receive noise, receive nonlinearities, and receive IQ mismatch, that limit the mitigation of self-interference. In [3], the authors experimentally demonstrated that Phase Noise in the local oscillator at the RF component is one of the bottlenecks that prevent self-interference cancelation. This is due to that phase noise in the local oscillator make the cancelling signal not perfectly null the self-interference signal, even small phase noise may degrade greatly the self-interference cancelation.

This paper makes a contribution to analyze and solve one of the factors that limits the self-interference cancelation: thermal noise. It is very hard to eliminate the impact of thermal noise on the Full-Duplex system by estimation actually, because different frame will be affected by independent thermal noise. However, we can improve the channel estimation by relatively increasing the power of long training symbols to reduce the impact of thermal noise naturely existing in the transmitter and receiver. Therefore, we propose a little modification and to redesign the data packet of the IEEE 802.11g. The potential performance of the proposed system is estimated by using ADS-Matlab co-simulation.

The rest of the paper is organized as follows. In Section II, we firstly describe the system model, and then the channel estimation and redesign of the data packet. After that, the residual self-interference is expressed mathematically following the self-interference cancelation model. The ADS-Matlab co-simulation results are presented in Section III. Finally, we draw the conclusions in Section IV.

II. System Description

The Full-Duplex OFDM wireless system developed in this paper is based on the active analog self-interference cancelation (AASIC) at the RF components which is implemented by constructing cancelation signal via the self-interference channel estimation and the knowledge of the transmit signal as in [4].

A. Signal Model

OFDM based IEEE 802.11g transmission is chosen as the physical layer in this paper. Perfect frequency and timing synchronization and no RF impairment are assumed, i.e. we just take the factor of thermal noise into consideration. At the receiver side, after the down-conversion of the RF signal received, the sample of the OFDM symbol in the digital domain can be represented as

$$r_m(n) = \sqrt{P}\sqrt{L} \cdot x_m(n) \otimes h_m(n) + \sqrt{P_{si}}\sqrt{L_{si}} \cdot x_{si,m}(n) \otimes h_{si,m}(n) + \xi_m(n), 1 \leq n \leq N_{CP} + N \quad (1)$$

where P and P_{si} represent the transmit power of the expected signal and self-interference signal, L and L_{si} denote the propagation loss of the expected link and self-interference link, variables $x_m(n)$ and $x_{si,m}(n)$ denote the transmitted symbol of the distance node and local node respectively, while $h_m(n)$ and $h_{si,m}(n)$ are the channel impulse response of the distance link and self-interference link. The term $\xi_m(n)$ represents thermal noise at the receiver with variance δ_n^2. N_{CP} is the length of the cyclic prefix.

In the frequency domain, after removing the N_{CP} samples corresponding to cyclic prefix and taking the FFT on the remaining N symbols, the m^{th} demodulated OFDM symbol is given by

$$R_m[k] = \sqrt{P}\sqrt{L} \cdot X_m[k]H_m[k] + \sqrt{P_{si}}\sqrt{L_{si}} \cdot X_{si,m}[k] \cdot H_{si,m}[k] + \zeta_m[k], 1 \le k \le N \quad (2)$$

where $X_m[k]$ and $X_{si,m}[k]$ denote the transmitted symbol carried by the k^{th} subcarrier from the distant node and local node respectively. $H_m[k]$ and $H_{si,m}[k]$ represent the transfer function at the k^{th} subcarrier frequency of the expected link and self-interference link. $\zeta_m[k]$ corresponds to the frequency domain expression of $\xi_m(n)$. $X_m[k]$ can be treated as mutually independent random variables independent of $H_m[k]$ and $\zeta_m[k]$ with zero mean and variance $E\{|X_m[k]|^2\} = 1$. $X_{si,m}[k]$ has the same characterization as the $X_m[k]$. Without loss of generality, the transfer function $H_m[k]$ and $H_{si,m}[k]$ are normalized and with average channel gain $E\{|H_m[k]|^2\} = E\{|H_{si,m}[k]|^2\} = 1$.

B. Channel Estimation and Redesign of the Data Packet for Enhancing

For IEEE 802.11g standard, each data packet consists of two parts: preamble and data. The preamble includes short and long training symbols which are used, e.g., for synchronization, frequency offset and channel estimation. Generally, the preamble and the data symbols are transmitted with the same power and the channel state information (CSI) is estimated by dividing the long training symbols received and demodulated pilot pattern with the known symbol sequences $P[k], k \in [1, N]$. In order to avoid the self-interference channel estimation error caused by the expected signal, the long training symbols from different nodes are transmitted at different time slots. Therefore, the estimated channel transfer function after normalization can be expressed as

$$\widetilde{H}_{si,m}[k] = H_{si,m}[k] + \zeta_m[k]/(\sqrt{P_{si}^{lts}}\sqrt{L_{si}} \cdot P[k]) \quad (3)$$

where P_{si}^{lts} represents the transmit power of the long training symbols. The second term at the right of the equation (3) is denoted as channel estimation error η^k of the k^{th} subcarrier due to thermal noise.

Our works will demonstrate that active self-interference cancelation (ASIC) has high requirement on the self-interference channel estimation. Even small channel estimation error causes unnegligible residual self-interference. Here, we use the Normalized Mean Square Error (NMSE) as the criteria to assess the performance of channel estimation. The NMSE is defined as

$$NMSE = \frac{\sum_k |\widetilde{H}_{si,m}[k] - H_{si,m}[k]|^2}{\sum_k |H_{si,m}[k]|^2} \quad (4)$$

The higher the power ratio of interference to thermal noise (INR) of the self-interference link is, the better quality of channel estimation can be achieved. We get the estimated coefficients of subcarrier channel of the self-interference link from the ADS channel estimator and draw the Figure. 1. via equation (4). As shown in Figure. 1., a $10dB$ increase of INR make almost $10dB$ reduction of NMSE.

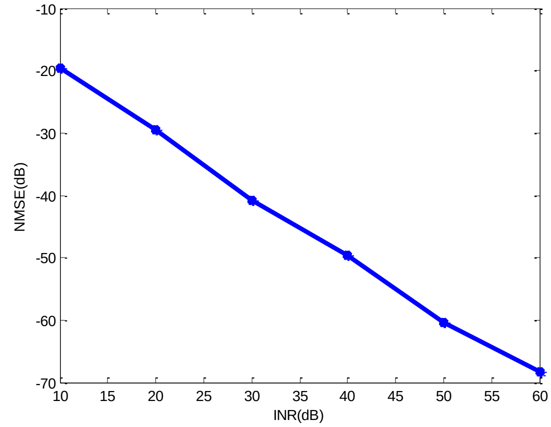

Fig. 1. NMSE of the self-interference channel estimation vs. INR

Given the power of the thermal noise is fixed, more accurate channel estimation can be obtained by improving the power of long training symbols due to the fact that: the higher the power ratio of signal to noise is, the better channel estimation can be achieved. Therefore, we propose to set the magnitude of the long training symbols as α times of the magnitude of the data symbols, which is expressed mathematically as

$$\sqrt{P_t^{lts}} = \alpha\sqrt{P_t} \quad (5)$$

Therefore, we redesign the data packet for enhancing channel estimation to further reduce the self-interference. The structure of the data packet redesigned is shown in Figure. 2.

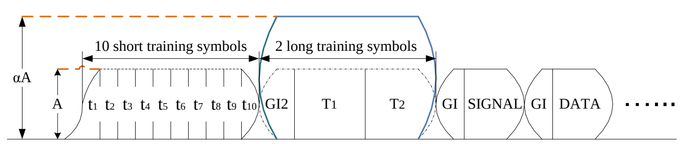

Fig. 2. Structure of the redesigned data packet

C. Self-interference Cancelation Model

With the estimated CSI (channel state inforamtion) of the self-interference channel, the self-interference cancelation is done by substracting the cancelation signal $\sqrt{P_{si}}\sqrt{\widetilde{L}_{si}}X_{si,m}[k]\widetilde{H}_{si,m}[k]$ from the received signal. After the interference cancelation, the residual self-interference can be represented by

$$R_{m,res} = \sqrt{P}\sqrt{L} \cdot X_m[k]H_m[k] + \sqrt{P_{si}}\sqrt{L_{si}} \cdot X_{si,m}[k] \cdot H_{si,m}[k] - \sqrt{P_{si}}\sqrt{\widetilde{L}_{si}}X_{si,m}[k]\widetilde{H}_{si,m}[k] + \zeta_m[k] \quad (6)$$

Here, we make the assumption that $\widetilde{L}_{si} = L_{si}$, because L_{si} is the propagation loss and we get the estimation of it accurately by previous measurement. Then, we combine the equation (3) and (6) and express the residual self-interference as

$$R_{m,res} = \sqrt{P}\sqrt{L}X_m[k]H_m[k] - \frac{\sqrt{P_{si}}X_{si,m}[k]}{\sqrt{P_{si}^{lts}}P[k]}\zeta'_m[k] + \zeta_m[k] \tag{7}$$

D. Residual Self-interference

Because of the independence between $\sqrt{P_{si}}$, $\sqrt{P_{si}^{lts}}$, $X_{si}[k]$ and $P[k]$ in equation (7), the power of the residual self-interference can expressed as

$$\begin{aligned} P_{si,residual} &= \frac{P_{si}}{P_{si}^{lts}}\delta_n^2 \\ &= \frac{1}{\alpha^2}\delta_n^2 \end{aligned} \tag{8}$$

Therefore,

$$P_{si,residual} = \begin{cases} > \delta_n^2, & \text{if } \alpha < 1 \\ = \delta_n^2, & \text{if } \alpha = 1 \\ < \delta_n^2, & \text{if } \alpha > 1. \end{cases} \tag{9}$$

From the equation (9), we can get that the residual self-interference equals δ_n^2 [4] when $\alpha = 1$ which means the long training symbols are transmitted with the same power level as the data symbols. This is a common scenario in current practical WiFi implementation. However, the residual self-interference can be reduced to under noise level by setting higher power level to the long training symbols than the power level of the data symbols, namely $\alpha > 1$. This power-difference method works better in the low INR scenarios which will be demonstated in the results.

III. Results

We model the Full-Duplex OFDM wireless system with single path one delay self-interference channel based on the co-simulation between the software Advanced Design System (ADS) and Matlab. ADS can provide us complete wireless system model and close-to-reality research results, while Matlab can help us to more flexibly deal with the digital signal processing. The system parameter is chosen for $36Mbps$ WiFi link from the IEEE 802.11g standard.

As shown in Figure 3., when the power put on the long training symbols is equal to the power of data symbols, i.e. $\alpha = 1$, the BER curves of the distance link with different level of self-interference signal almost overlap with each other. This can be explained by equation (8) and (9). The channel estimation error due to the thermal noise causes almost $3dB$ residual self-interference to the distance link. After employing our power difference method, there is just $1.5dB$ residual self-interference.

As can be seen in Figure 4., there are $5dB$ residual self-interference when $INR = 5$ if $\alpha = 0dB$, which means there is no self-interference suppression by using ASIC if $\alpha = 0dB$ when INR is low. This can be explained by the fact that the channel estimation is not accurate enough to implement the ASIC for Full-Duplex wireless when INR is low. However, we can reduce the residual self-interference when INR is low to the level to which the high INR Full-Duplex wireless system can achieve. From the Figure 4., the residual self-interference is reduced by $2.5dB$ via increasing the α from

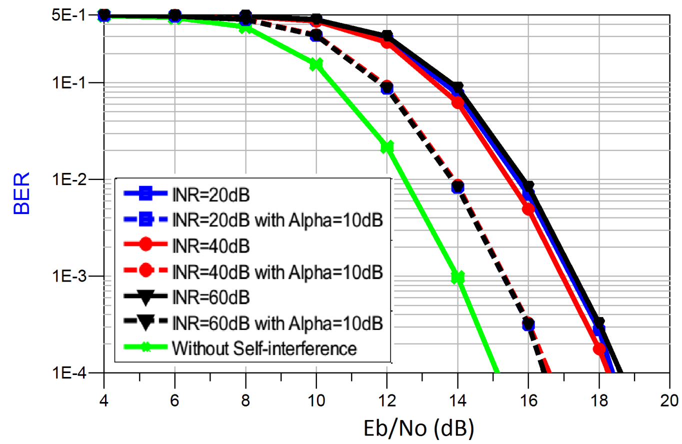

Fig. 3. The BER comparison of Full-Duplex wireless for different INRs

$0dB$ to $2.5dB$; when α increase to $5dB$, the residual self-interference is around $1.7dB$. If we further increase α, the strength of the residual self-interference comes to $1.5dB$.

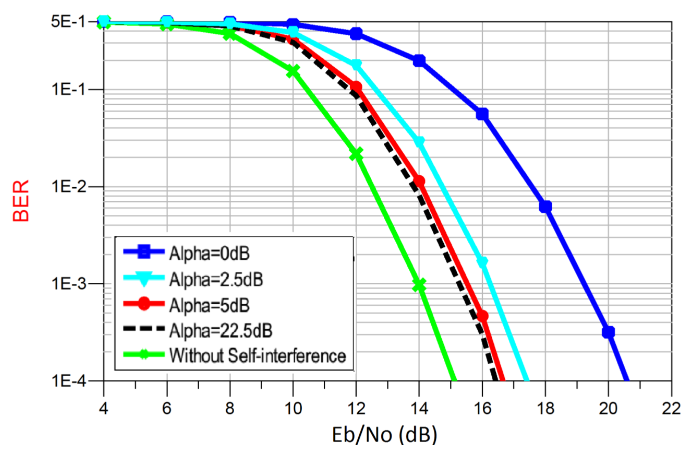

Fig. 4. The BER of Full-Duplex wireless for INR=5dB with different α

IV. Conclusion

In this paper, one of the factors: thermal noise, limiting the active self-interference suppression for the Full-Duplex wireless system, is analyzed and demonstrated. Besides, we propose a power difference method to reduce the impact of thermal noise on the Full-Duplex OFDM Radio.

References

[1] M. Duarte, C. Dick, and A. Sabharwal, Experiment Driven Characterization of Full-Duplex Wireless Communications, IEEE Trans. Wireless Commun., vol.11, no. 12, pp4296-4307,Dec.2012.

[2] D.W. Bliss, T.M. Hancock, and P.Schniter, “Hardware Phenomenological Effects on Cochannel Full-Duplex MIMO Relay Performance,”in IEEE Asilomar Conference on Signals, Systems and Computers, Nov. 2012, pp. 34-39.

[3] Achaleshwar Sahai, Gaurav Patel, Chris Dick and Ashutosh Sabharwal, “On the impact of Phase Noise on Active Cancellation in Wireless Full-Duplex” arXiv preprint arXiv:1212.5462, 2012.

[4] Zhaowu Zhan, Guillaume Villemaud and Jean-Marie Gorce, “Design and Evaluation of a Wideband Full-Duplex OFDM System Based on AASIC,” to appear in IEEE PIMRC 2013.