Self-adaptive over-the-air RF self-interference cancellation based on signal-of-interest driven regular triangle algorithm

Lizhuo Zheng, [1] Zhiyang Liu,[1] Shilin Xiao,[1] Zhiyi Zhang, [1] Qidi Liu[2] and Mable P. Fok[2,*]
[1]The State key laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China
[2]Lightwave and Microwave Photonics Laboratory, College of Engineering, University of Georgia, Athens, Georgia 30602, USA
**Corresponding author: mfok@uga.edu*

Abstract: A signal-of-interest driven self-adaptive RF self-interference cancellation system has been proposed based on regular-triangle algorithm. A weak 16-QAM OFDM signal-of-interest at 18.35GHz has been successfully retrieved with small converge steps in an in-band full-duplex transmission.
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1. Introduction

To solve the problem of RF spectrum scarcity, in-band full-duplex transmission is a promising solution to double the spectral efficiency and enlarge the communication capacity of RF communication systems. In-band full-duplex transmissions require the use of the same frequency for both transmission and receiving at the node. Unfortunately, sharing the same frequency for transmission and receiving in an over-the-air scenario makes it impossible to properly receive the remote weak signal-of-interest (SOI) due to the strong self-interference from the local transmission antenna. Since both the self-interference signal and the SOI share the same frequency, the SOI is completely masked by the interference signal in both temporal and spectral domains, even a spectral filter will not be able to remove it, resulting in a complete corruption of the SOI [1]. RF communication systems cannot benefit from in-band full-duplex transmission unless the self-interference signal can be effectively removed and retrieve the SOI.

In recent years, intensive research on both electronics [2] and photonics [3] based self-interference cancellation (SIC) systems have been performed and is promising for removing the strong self-interference signal. The idea is same as the noise-cancellation headset, where a weighted and delayed copy of the local interference signal is subtracted from the received signal that consists of both the weak SOI and the strong interference signal, leaving behind the SOI. The success of retrieving the SOI greatly depends on how precise the SIC system can weight and delay the local interference signal copy and match it with the received interference signal for subtraction. A number of manually tunable SIC systems have achieved outstanding wideband cancellation in cable testing and adaptive algorithms are being used in the absence of the SOI; however, a realistic communication system consists of antennas and dynamic transmission channels that causes dynamic signal mismatch and could significantly degrade the cancellation performance. Thus, it is essential to be able to self-adapt to the changing transmission environment in an over-the-air scenario to obtain real-time optimization of the cancellation performance and retrieving the SOI in a realistic and dynamic environment.

In this paper, we proposed and experimentally achieved the first demonstration of SOI driven regular triangle (RT) algorithm for self-adaptive over-the-air self-interference cancellation. Since retrieving of SOI is the main goal of a SIC system, using the SOI to train the self-adaptive algorithm makes a natural sense. Unlike other power based adaptive algorithms that optimize the SIC based on the self-interference power, using the quality of SOI as the training parameter ensures that the SIC is converged to its optimal cancellation point to provide the best cancellation at the SOI frequency. Regular triangle algorithm [3] only requires a small number of steps for optimization to enable a fast converging process. We experimentally demonstrated an over-the-air self-interference cancellation at 18.35 GHz with a cancellation depth of 22 dB over a 300 MHz bandwidth, and have enabled self-adaptation to successfully retrieve the 16 QAM orthogonal frequency division multiplexing (OFDM) signal to achieve a 10^{-6} to 10^{-12} bit-error rate (BER), which is by far the highest cancellation frequency demonstrated in over-the-air transmission.

2. Principle and Experimental Setup

Fig. 1(a) illustrates the architecture of the proposed self-adaptive over-the-air self-interference cancellation system, which consists of (i) over-the-air transmission module, (ii) self-interference cancellation (SIC) module [3], and (iii) self-adaptive control module. The over-the-air transmission module consists of a transmission antenna Tx1 and a receiving antenna Rx1 at node 1. Rx1 is trying to receive the remote SOI from Tx2 at node 2, however, the Rx1 is also receiving a strong self-interfering signal from the local Tx1. Horn antennas with frequency range from 7 GHz to 25 GHz are used in the experiment. Tx1 is transmitting a 300-Mbaud/s OFDM signal while Tx2 is transmitting a 200-Mbaud/s OFDM signal at 18.35 GHz as SOI, both generated from the arbitrary waveform generator (AWG Keysight M8195A). A portion of the signal from the local antenna Tx1 is tapped and will be used as the reference signal for the SIC module. The self-interference cancellation module consists of two electro-absorption modulated lasers (EML 1 and EML 2) to convert the received RF signal from Rx1 and the reference signal into optical domain. Weighting and temporal delay are performed using the tunable optical attenuator and tunable optical delay with 25 dB and 660 ps tuning range, respectively. A balanced photodetector (BPD) is used for subtracting the self-interference signal from the received signal, such that a clean SOI can be obtained. The self-adaptive control module consists of a computer running the SOI driven regular triangle algorithm in MATLAB for controlling the tunable optical delay and tunable attenuator. An Ethernet switch enables the computer to simultaneously control the AWG and receive data from the oscilloscope/receiver (LeCroy SDA845Zi-A).

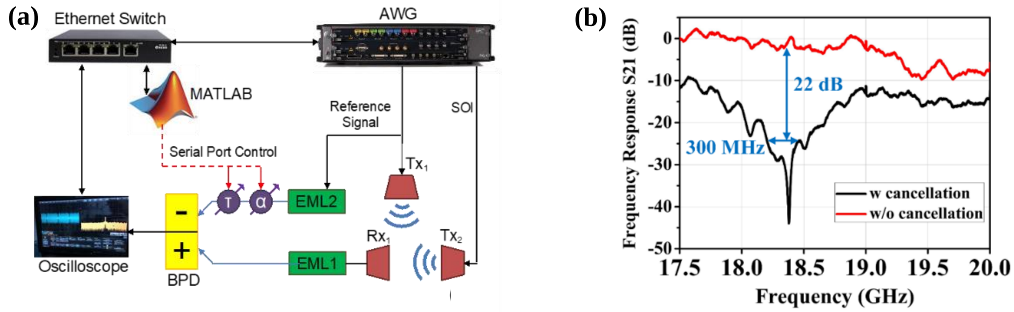

Fig. 1 (a) Experimental setup of the self-adaptive over-the-air self-interference cancellation system; EML 1-2: electro absorption modulated lasers; BPD: balanced photodetector; AWG: arbitrary waveform generator; SOI: signal of interest; (b) S21 frequency response of the over-the-air transmission system with and without the enabling of SIC.

A 2^{12}-1 pseudo-random binary sequence OFDM signal is used to train the SOI-driven regular triangle algorithm, when real data is not transmitting. Output of the BPD monitored by the oscilloscope is launched to the computer for digital down-conversion. The computer uses the BER of the OFDM signal to train the SOI driven regular triangle algorithm. SOI-driven regular triangle algorithm considers the adaptive process as a convex problem within the maximum range of the independent variables (delay and attenuation) and has only one minimum point (BER of SOI) [3]. The algorithm starts by calculating the BER at each original regular triangle angle and identifying the minimum, then it continues to move towards the minimal direction and calculates the BER at a +/-30º angles for identifying the optimized converging direction and repeats. The SOI-driven regular triangle algorithm converges the BER of the training SOI to a minimum through the automatic control of the tunable attenuator and delay (i.e. precise matching between the reference signal and the received self-interference signal). To get an idea of the best cancellation performance, frequency response of over-the-air transmission with and without the enabling of SIC is measured using a 10 MHz - 43.5 GHz vector network analyzer (VNA Keysight N5224A) and is shown in Fig. 1(b). A 22-dB cancellation depth is obtained over a 300 MHz bandwidth at 18.35 GHz. Table 1 shows a comparison between various over-the-air SIC and adaptive schemes. According to Table 1, our scheme is the first over-the-air demonstration of self-adaptive SIC system, that also has the highest cancellation frequency for in-band full-duplex transmission without the need of post-DSP cancellation. The SOI based regular triangle algorithm also has the smallest number of steps for convergence compared with other adaptation schemes.

Table 1. Comparison of various over-the-air and self-adaptive self-interference cancellation schemes

Approach	Over-the-air	f_c (GHz)	Cancellation Depth (dB)	Self-Adaptive	Number of Steps	Requires Post-DSP cancellation	Cancellation Bandwidth
This paper	Yes	18.35	22	Yes	11	No	300MHz
[4]	Yes	11	22	No	-	No	300MHz
[5]	Yes	9.85	30	No	-	Yes	400MHz
[6]	Yes	20	28-30	No	-	Yes	400MHz
[7]	Yes	12.33	30	No	-	Yes	1.22GHz
[8]	Yes	2.4	22	No	-	No	130MHz
[9]	Yes	2.39	30	No	-	No	20MHz
[3]	No	0.8	20	Yes	13	No	300MHz
[10]	No	0.7	22	Yes	17	No	700MHz
[11]	No	1.963	50	Yes	70	No	20MHz

3. Results and Discussion

To study the performance of the self-adaptive process in an over-the-air transmission scenario, 300-MBaud/s and 200-Mbaud/s 16-QAM OFDM signals at 18.35 GHz are used for transmission at Tx1 and Tx2 as self-interference signal and SOI signal, which are completely overlapping in the spectral domain. Here, the bandwidth of self-interference signal is set to be wider such that it is completely masking the SOI spectrally. Due to the proximity of the Tx1 to Rx1, the receiver Rx1 is receiving a strong self-interference signal from Tx1 but a weak SOI from Tx2. Therefore, the SOI is completely buried by the in-band self-interference signal and cannot be distinguished in neither the spectral domain nor in time domain, resulting in a poor BER as shown by point A in Fig. 2(a). The measured RF spectrum is shown in inset (I) in Fig. 2(a) that only the self-interference signal spectrum is visible while that of the SOI is completely buried underneath. The corresponding constellation diagram is shown in Fig.2 (b)I, which is impossible to identify the constellation at all. As the adaptive process proceeds as shown by the red curve in Fig. 2(a), the self-adaptive SIC system gradually converges to the optimal point that results in a BER of 10^{-6} or below, meaning that the SOI is fully recovered. Point B and C in Fig. 2(a) show the points during the converging process, while inset (II) shows the corresponding spectrum of the SOI emerges from the strong self-interference signal spectrum as the iteration increases and becomes partially invisible in the spectral domain. Fig. 2(b)ii-iii are the corresponding constellation diagrams showing that the 16 QAM OFDM SOI is starting to become recognizable. Finally, as the self-adaptive process reaches the optimal point, BER is at 10^{-6} or below is achieved and the self-interference signal is completely suppressed in spectral domain, leaving behind the SOI spectrum, as shown by point D and inset (III) of Fig. 2(a). A clear constellation diagram is also resulted as shown in Fig. 2(b)iv. It is worth to notice that the SOI-based regular triangle algorithm can converge from different starting points in the converging space. The blue curve in Fig. 2(a) shows another example of the converging process. Various starting points have been tested and the maximum iteration number is 11, showing that the SOI driven regular triangle algorithm has a fast converging time compared with other schemes in Table 1.

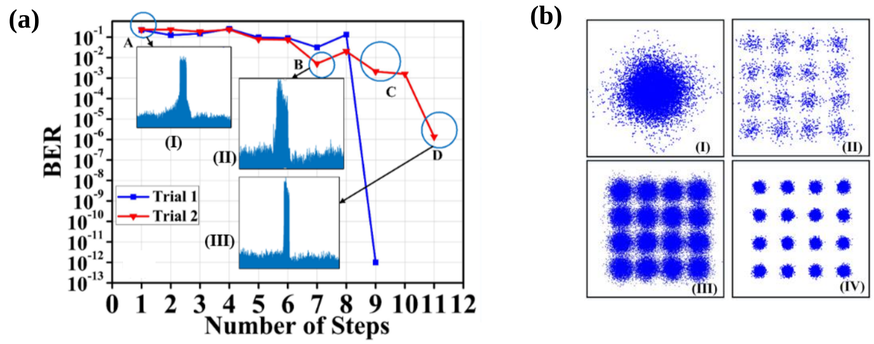

Fig. 2 Convergence process of the SOI-driven self-adaptive SIC system for over-the-air transmission. (a) BER measurement and RF spectra (b) Corresponding constellation diagrams of the OFDM SOI.

4. Conclusion

A SOI-driven regular triangle algorithm has been proposed and demonstrated for self-adaptive over-the-air self-interference cancellation. The over-the-air self-adaptive SIC system is trained and optimized by a 200 Mbaud/s OFDM SOI signal at 18.35 GHz to enable in-band full-duplex transmission. With the help of the SOI-driven regular triangle algorithm, the OFDM signal at 18.35 GHz has been successfully retrieved even under the interference of a strong in-band local transmitting signal. The SOI-driven regular triangle algorithm has a small iteration time and is a natural optimization approach to retrieve the SOI.

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