Performance of Self-Interference Canceller in SDR-Based Full-Duplex System

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***Abstract*—To realize full-duplex mobile system, the key challenge is to eliminate the self-interference (SI) caused by the coupling between the transmitter (TX) and its own receiver (RX). We propose a new type of SI canceller using a specific demodulation reference signal (DMRS) which can estimate the channel response of SI. First, the DMRS mapping shift method which enables SI cancellation is described. Then, the principle of proposed SI canceller using the DMRS mapping shift method. Furthermore, we show the configuration of SDR-based full-duplex system combining analog front end and FPGA introduced the algorithm of the proposed SI canceller. We demonstrate the BERs of OFDM signal whose symbol modulations are up to 1024-QAM under the presence of enormous amount of SI. The experimental results verify that the proposed SI canceller can sufficiently improve the BERs of OFDM signal.**

Keywords—full-duplex mobile system, self-interference canceller, DMRS mapping, SDR, FPGA

I. Introduction

Duplex is one of most important technologies for mobile communication systems to separate downlink (DL) and uplink (UL) from the time and spectrum assignments perspective. Fifth-generation (5G) mobile systems are mostly operated by time division duplex (TDD) communication on the same carrier frequency, and fourth-generation (4G) mobile systems uses almost frequency division duplex (FDD) communication worldwide. Thus, current mobile systems operate in half-duplex communications [1]–[3].

TDD and FDD have some pros and cons mutually. TDD provides better spectral efficiency compared with FDD, however, simultaneous transmission between base station (BS) and user equipment (UE) cannot be allowed in TDD frame structure. While, FDD can allow the simultaneous transmission because the carrier frequency band in DL is different from that in the UL.

Over the past few years, full-duplex mobile communications have been discussed to increase the spectral efficiency as a technology candidate for 5G mobile systems and beyond. The full-duplex mobile communications can transmit and receive simultaneously on the same carrier frequency in both DL and UL. Consequently, the DL signal from BS to UE and the UL signal from UE to BS can transmit simultaneously on the same carrier frequency. However, in that case, self-interference (SI) is caused by the coupling between the transmitter (TX) and its own receiver (RX). For example, the transmit signal at BS in DL interferes the UL signal from UE at the BS receiver. Similarly, the transmit signal at UE in UL interferes the DL signal from BS at the UE receiver. Thus, SI must be cancelled or eliminated for realizing full-duplex mobile communications. The SI is preferable ultimately less than noise and interference to achieve the required link signal-to-interference plus noise ratio (SINR). In the past, the SI was considered not to be cancelled because its power was too strong to overcome [4].

Time domain analog/digital SI cancellation technologies were proposed using a training signal, which can estimate the SI leakage response. In analog SI cancellation, attenuator and phase shifter are used to create the replica signal of the SI leakage. The target of digital SI cancellation is to eliminate the residual SI after the analog cancellation, because the analog SI cancellation cannot perfectly cancel the SI [5]–[12]. SI is challenge even in the relay technology, especially for in-band relaying [13, 14]. In [14], fiber-optic relaying with simultaneous transmission and reception on the same carrier frequency has been investigated possible to realize full-duplex relay schemes, although no SI cancellation is required from the cost effectiveness perspective.

These SI cancellation architectures are not sufficiently from the useful and practical control perspective. In [15], we have proposed a SI canceller using a demodulation reference signal (DMRS) which can estimate the channel response of SI, although conventional DMRS defined in 5G is used to estimate the channel response for the DL and UL, i.e., the link between BS and UE.

We have been investigating the performance of the proposed SI canceller operated only at baseband, however analog front end is not included. In this paper, we present the performance of proposed SI canceller experimentally using a software defined radio (SDR)-based full-duplex system. This system model combines analog front end and a field programmable gate array (FPGA) introduced the algorithm of the proposed SI canceller. We demonstrate the BERs of orthogonal frequency division multiplexing (OFDM) signal under the presence of SI, where five types of symbol modulation methods, i.e., quadrature phase shift keying (QPSK), 16-, 64-, 256-, and 1024-quadrature amplitude modulation (QAM) are used [15]–[17]. This paper is organized as follows. In Section II, we describe the configuration of proposed SI canceller and SDR-based full-duplex system. In Section III, we demonstrate the BERs of OFDM signal. Finally, Section IV concludes our works.

II. Proposed SI Canceller

A. Mechanism of SI

In full-duplex mobile systems between BS and single UE, the DL and UL can operate simultaneously on the same carrier frequency. Figure 1 shows the mechanism of the occurrence of SI, where the DL interferes with the reception in the UL signal at the BS RX. Similarly, the UL signal interferes with the reception in the DL at the UE RX. The SI power is much higher relative to RX noise floor and desired signal power. Therefore, SI is required to cancel enough so that the power can be reduced almost the same level of the RX noise floor.

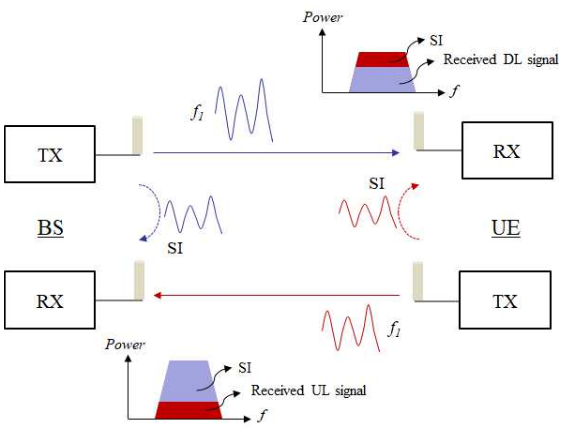


Fig. 1. Mechanism of SI occurence in full-duplex mobile systems.

B. Proposed SI canceller using DMRS

DMRS defined in 5G works for the channel estimation between BS and UE, and for demodulation of physical data channels. Multiple DMRS are mapped in each resource block, and the number of DMRS and mapping position are flexible.

We first prepare two types of DMRS mapping for SI canceller as shown in Fig.2. Blue-colored DMRS are mapped for DL channel, while red-colored DMRS are mapped for the UL channel so as not to overlap each other.

Figure 3 shows the proposed SI canceller using blue-colored DL DMRS located at BS. The DL signal interferers as SI with the reception in the UL signal from UE. The DL DMRS works for the estimation of the channel response of SI, comparing the transmit blue-colored DL DMRS with the received blue-colored DL DMRS contained in the SI. The amplitude and phase of each TX data are adjusted using the obtained channel response of SI. Then, SI canceller subtracts the adjusted TX data from the UL received signal. Finally, the desired UL signal after SI cancellation is demodulated through the use of UL channel estimation and equalizer using red-colored UL DMRS.

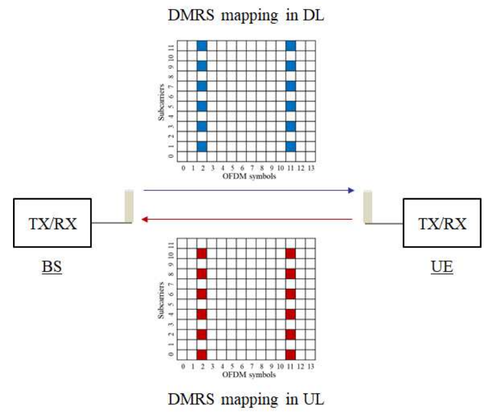


Fig. 2. DMRS mapping for DL and UL.

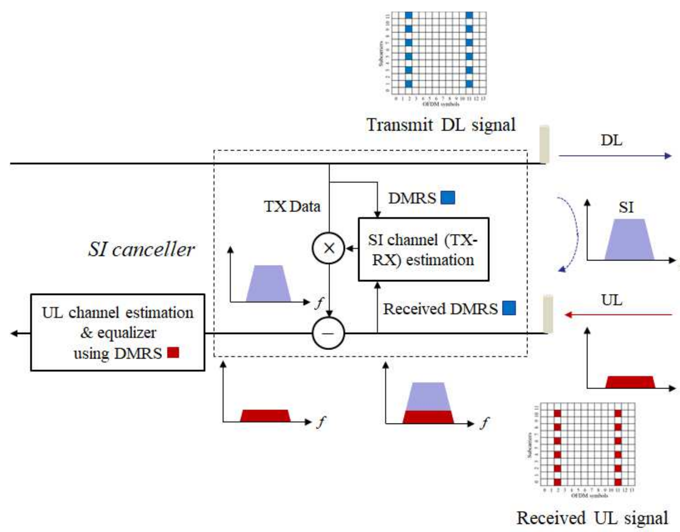


Fig. 3. Proposed SI canceller using DMRS.

C. SDR-based experiment system

We first design a simulation block diagram of BS and UE using MATLAB/Simulink, which are used for algorithm development, hardware architecture, and code generation, as shown in Fig. 4. Here, BB-TX and BB-RX stand for baseband transmitter and baseband receiver, respectively, and these are basically designed by 5G specifications. The BB-TX of BS TX is same as that of UE TX except a gain adjustment. The gain adjustment decides the desired-to-undesired-signal ratio (DUR), which is defined as the ratio between UL received signal power from UE and SI power.

We then development SDR system combining analog front end and FPGA. The FPGA is programmed by driving data from MATLAB/Simulink models as shown in Fig. 4. Figure 5 shows the configuration of SDR-based experiment system with analog front end operating at an intermediate frequency (IF) of 450 MHz band as well as FPGAs, where digital-to-analog (D/A) converter is operated at 12 GHz, and analog-to-digital (A/D) converter is operated at 4 GHz with 12 bits resolution [18]. The BB-TX output of FPGA in BS TX is input to a combiner as SI by way of the D/A and up-converter. The BB-TX output of FPGA in UE TX is also input the combiner as desired signal by way of the D/A and up-converter. Then, the combined signals are input to the BS RX. The SI is cancelled by SI canceller located at BS. Preamble signals are added to the BB-TX data for both BS TX and UE TX to decide receiver windows.

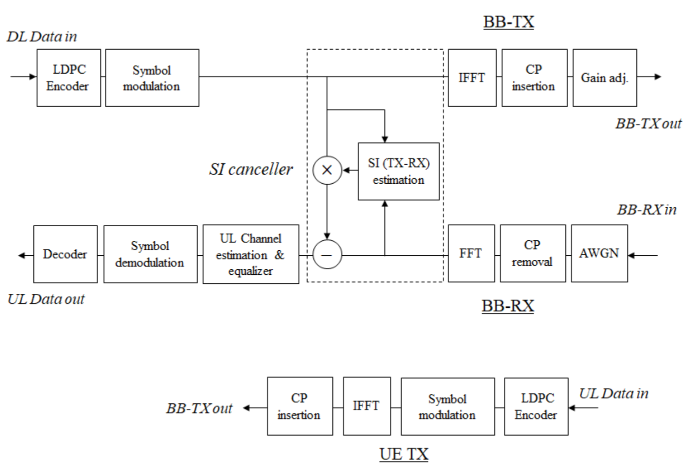


Fig. 4. Block diagram of BB-TX and BB-RX with SI canceller.

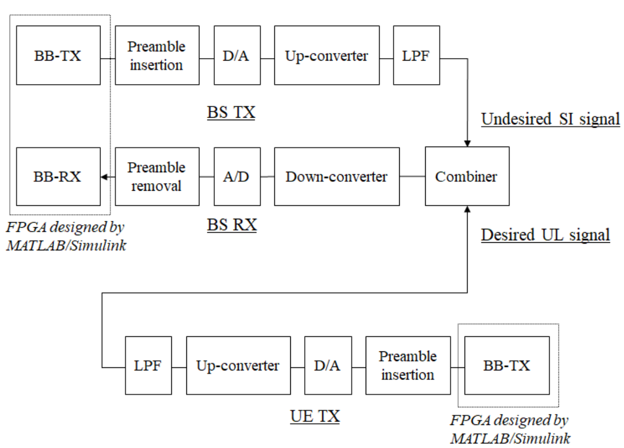


Fig. 5. SDR-based experiment system.

III. Experimental Results

A. SDR system setup

The primary parameters of BB-TX and BB-RX are listed in Table I. The signal bandwidth of OFDM is 100 MHz with the subcarrier spacing of 30 kHz. Low-density parity-check (LDPC) is used for encoder which is typically used in 5G. DMRS for DL and UL are mapped in time domain at OFDM symbols 2 and 11. However, DMRS mapping for DL in frequency domain is different from that for UL. The DMRS for DL (blue-color) are mapped on the odd-number subcarriers, i.e., 1, 3, 5, 7, 9, and 11 at OFDM symbols 2 and 11. The DMRS for UL (red-color) are mapped on the even-number subcarriers at OFDM symbols 2 and 11. The parameters of analog front end, D/A, A/D, and preamble signals are listed in Table II. Single antenna is assumed for both TX and RX antennas for simplicity.

TABLE I. Primary Parameters of BB-TX and BB-RX

Parameter	Value
Encoder	LDPC
Symbol modulation	QPSK to 1024-QAM
Signal mapping	Gray code
System bandwidth	100 MHz
OFDM subcarrier spacing	30 kHz
FFT size	4096
Sampling rate	122.88 MHz
DL DMRS mapping	OFDM subcarriers 1,3,5,7,9,11 OFDM symbols 2, 11
UL DMRS mapping	OFDM subcarriers 0,2,4,6,8,10 OFDM symbols 2, 11
Cyclic prefix length	2380 ns

TABLE II. Parameters of Front End, D/A, and A/D

Parameter	Value
IF band	450 MHz
Preamble	Modulation : QPSK FFT size : 4096 Symbol length : 33.33 ms
A/D	4 GHz, 12 bits
D/A	12 GHz, 16 bits
The order of LPF	48

B. BER performance

We verify the effect of proposed SI canceller by measuring BER as well as by monitoring the signal constellation. Figure 6 shows the observed instantaneous OFDM frequency spectrum of desired UL signal and undesired SI signal in the case of a DUR of −60 dB. Figure 7(a) shows photos of QPSK and 1024-QAM signal constellations at transmitter side, i.e., BB-TX out at UE TX. Figure 7(b) shows the signal constellation of QPSK and 1024-QAM at receiver side, i.e., BS RX, after SI cancellation. From these results, it is predicted that the proposed SI canceller can eliminate enormous amount of SI and enough to demodulate the desired signal.

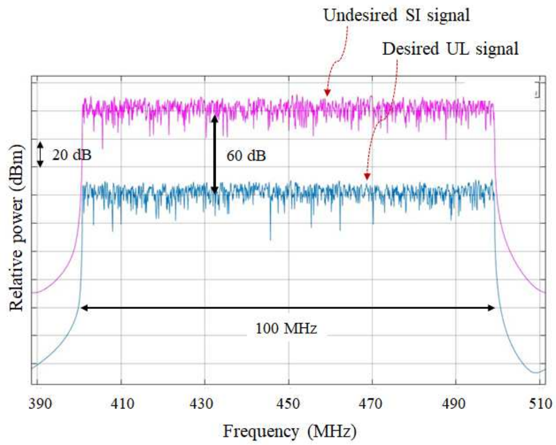
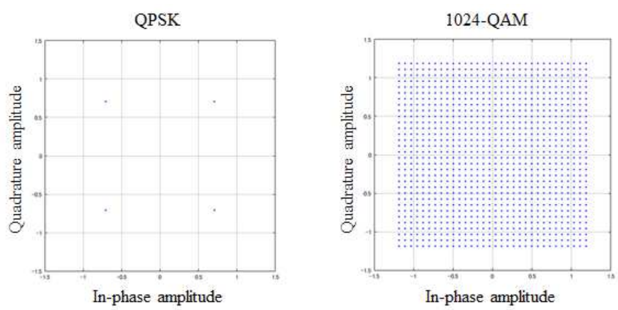
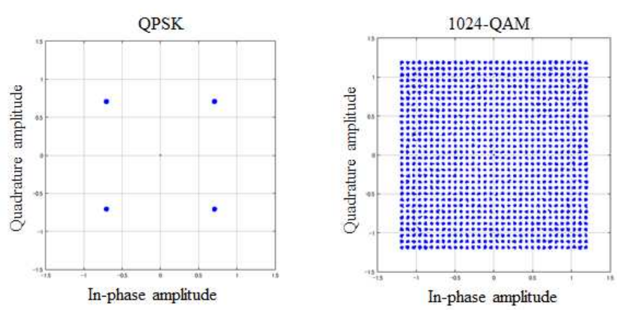


Fig. 6. Desired UL and Undesired SI signals at a DUR of −60 dB.



(a) Transmitter side (BB-TX out at UE TX)



(b) Receiver side at BS RX after SI cancellation.

Fig. 7. Signal constellations at a DUR of −60 dB.

TABLE III. DOWNLINK MCS INDEXES USED IN THE SIMULATION

MCS Index	Modulation	Coding rate R = x/1024	Efficiency (bits/Hz)
1	QPSK	602	1.1758
2	16-QAM	658	2.5703
3	64-QAM	873	5.1152
4	256-QAM	948	7.4063
5	1024-QAM	938.7	9.1670

BERs are measured for five types of modulation and coding scheme (MCS), i.e., from MCS indexes 1 to 5, as shown in Table III. Here, MCS index 1 means the combination of QPSK and the coding rate of 502/1024. Figures 8 and 9 show BERs against received SNR for five types of MCS at a DUR of −60 and −90 dB, respectively. If the SI canceller does not work (SI canceller OFF), desired UL signal can no longer be demodulated under the presence of SI. When the SI canceller works (SI canceller ON), good BERs are obtained as shown in Figs. 8 and 9. Like these, the proposed SI canceller can improve BERs drastically under the presence of enormous amount of SI such as a DUR of −90 dB.

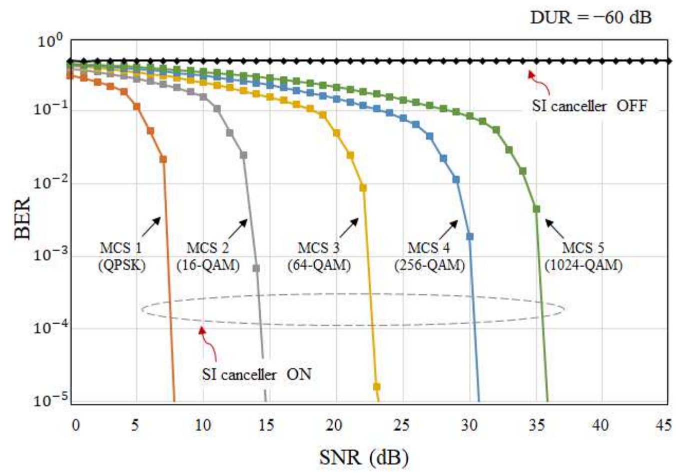


Fig. 8. BER performance at a DUR of −60 dB.

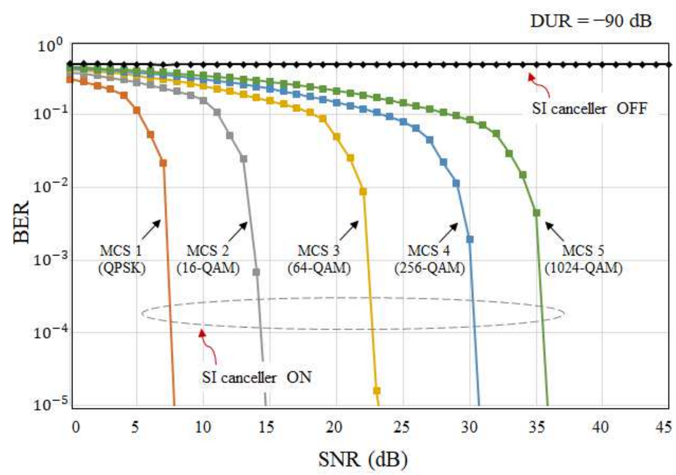


Fig. 10. BER performance at a DUR of −90 dB.

IV. CONCLUSION

In this paper, we first described the configuration of a new type of self-interference (SI) canceller for full-duplex mobile systems using a specific demodulation reference signal (DMRS). Next, we showed SDR-based full-duplex experiment system applying

FPGA introduced the algorithm of proposed SI canceller. Then using SDR-based experiment system, we demonstrated the BERs of OFDM signals whose symbol modulations are QPSK to 1024-QAM at a DUR of −60 and −90 dB. We confirmed that the proposed SI canceller can improve drastically BERs, i.e., work enough to demodulate desired signal for all symbol modulations under the presence of enormous amount of SI.

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REFERENCES

[1] T. Nakamura, A. Benjebbour, Y. Kishiyama, S. Suyama, and T. Imai, "5G radio access: Requirements, concept and experimental trials," *IEICE Trans. on Commun.*, vol. E98-B, pp. 1397-1406, Aug. 2015.

[2] K. Balachandran, J. H. Kang, K. Karakayali, and K. M. Rege, "Flexible duplex in FDD spectrum," in *Proc. ICC workshops*, pp. 1-6, May 2017.

[3] 3GPP TR 23.501, "System architecture for the 5G system (5GS)," Release 15, June 2018.

[4] A. Goldsmith, Wireless Communications, *Cambridge University Press*, 2005.

[5] E. Ahmed, A. M. Eltawil, and A. Sabharwal, "Self-interference cancellation with phase noise induced ICI suppression for full-duplex systems," in *Proc. Globecom2013*, pp. 3384-3388, Dec. 2013.

[6] D. Bharadia, E. Mcmilin, and S. Katti, "Full duplex radios," *ACM Sigcomm Computer Commun. review*, vol. 43, no.4, pp.375-386, Oct. 2013.

[7] A. Sabharwal, P. Schniter, D. Guo, D.W. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: Challenges and opportunities (invited paper)," *IEEE J. on Selected Areas in Commun.*, vol. 32, no. 9, pp.1637-1652, Sept. 2014.

[8] Z. Zhang, X. Chai, K. Long, A. V. Vasilakos, and L. Hanzo, "Full duplex techniques for 5G networks: self-interference cancellation, protocol design, and relay selection," *IEEE Commun. Magazine*, vol. 53, no. 5, pp. 128-137, May 2015.

[9] R. Keating, R. Ratasuk, and A. Ghosh, "Performance analysis of full duplex in cellular systems," in *Proc. VTC2016-Spring*, pp. 1-5, May 2016.

[10] J. Zhou, T.H. Hao, T. Dinc, and H. Krishnaswamy, "Integrated Wideband Self-Interference Cancellation in the RF Domain for FDD and Full-Duplex Wireless," *IEEE J. of Solid-State Circuits*, vol. 50, no. 12, pp. 3015-3031, Dec. 2015.

[11] W. Wang and Z. Zhang, "DBF Based Channel Estimation for Self-interference Cancellation in Full-Duplex Communications," in *Proc. ICCCS2021*, pp. 564-569, April 2021.

[12] H. Harada, K. Mizutani, T. Matsumura, T. Kato, and K. Shioiri, "Development of Full-Duplex Cellular System for Beyond 5G and 6G Systems," in *Proc. PIMRC2022*, pp. 1-5, Sept. 2022.

[13] Y. Bo, L. Yang, X. Cheng, and R. Cao, "Transmit power optimization for full duplex decode-and-forward relaying," in *Proc. Globecom2013*, pp. 3347-3352, Dec. 2013.

[14] H. Utatsu and H. Otsuka, "Performance analysis of fiber-optic relaying with simultaneous transmission and reception on the same carrier frequency," *IEICE Trans. Commun.*, vol. E102-B, no. 8, pp.1771-1780, August 2019.

[15] T. Yasaka, T. Yamada, S. Suyama, and H. Otsuka, "Proposal of Self-Interference Canceller Using DMRS for Full Duplex Mobile Communications," in *Proc. VTC2023-Spring*, W9-8, pp. 1-5, June 2023.

[16] H. Otsuka, R. Tian, and K. Senda, "Transmission performance of an OFDM-based higher-order modulation scheme in multipath fading channels," *J. of Sensor and Actuator Networks*, vol. 8, no.2, pp. 1-15, March 2019.

[17] N. Inagaki, K. Yoda, T. Yasaka, S. Suyama, and H. Otsuka, "Impact of 3D-BF against the Number of Picocell Sector in mmWave HetNets," in *Proc. APWCS2023*, TS4-1, pp. 1-5, August 2023.

[18] AMD Xilinx Products, https://www.xilinx.com/products/boards-and-kits/zcu111.html.