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Analog Least Mean Square Loop
for Self-Interference Cancellation in In-Band Full-Duplex Radios

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A thesis submitted in partial fulfilment of the requirements for the degree of

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in
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by

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to

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AUTHOR'S DECLARATION

I, *Anh Tuyen Le* declare that this thesis, submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy, in the *School of Electrical and Data Engineering*, *Faculty of Engineering and IT* at the University of Technology Sydney, Australia, is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. This document has not been submitted for qualifications at any other academic institution. This research is supported by the Australian Government Research Training Program.

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List of Publications

Journals:

1. **A. T. Le**, L.C. Tran, X. Huang, and Y. J. Guo, “Beam-Based Analog Self-Interference Cancellation in Full-Duplex MIMO Systems," *IEEE Transactions on Wireless Communications*, vol. 19, no. 4, pp. 2460 - 2471, April 2020.

2. **A. T. Le**, L.C. Tran, X. Huang, and Y. J. Guo, “Analog least mean square loop for self-interference cancellation: A Practical Perspective," *Sensors*, vol. 20, no. 1, pp. 1-15, Jan. 2020.

3. **A. T. Le**, L.C. Tran, X. Huang, and Y. J. Guo, “Analog least mean square loop with I/Q imbalance for self-interference cancellation in full-duplex radios", *IEEE Transactions on Vehicular Technology*, vol. 68, no. 10, pp. 9848 - 9860, Aug. 2019.

4. **A. T. Le**, L.C. Tran, X. Huang, Y. J. Guo, and J. Vardaxoglou,“Frequency domain characterization and performance bounds of ALMS loop for RF self-interference cancellation", *IEEE Transactions on Communications*, vol. 67, no. 1, pp. 682-692, Jan. 2019.

5. **A. T. Le**, L.C. Tran and X. Huang, “Cyclostationary analysis of analog least mean square loop for self-interference cancellation in in-band full-duplex systems", *IEEE Communication Letters*, vol. 21, no. 12, pp. 2738-2741, Sept. 2017.

Conferences:

6. **A. T. Le**, L.C. Tran, X. Huang, and Y. J. Guo, “Analog least mean square loop for self-interference cancellation: Implementation and measurements," in *Proceedings of 29th International Telecommunication Networks Application Conference (ITNAC)*, Aukland, New Zealand, Nov. 2019, pp. 1-5 (Best Student Paper Award)

7. **A. T. Le**, L.C. Tran, X. Huang, and Y. J. Guo, “Beam-based analog self-interference cancellation with auxiliary transmit chains in full-duplex MIMO systems," *Proceedings of 2019 IEEE 20th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Cannes, France, July 2019, pp. 1-5

8. **A. T. Le**, L.C. Tran, X. Huang, Y. J. Guo, and J. Vardaxoglou,“Analog least mean square loop for self-interference cancellation in generalized continuous wave SAR," in *Proceedings of 88th IEEE Vehicular Technology Conference (VTC Spring)*, Chicago, USA, 2018, pp. 1-5

9. **A. T. Le**, L. C. Tran, and X. Huang, “On performance of analog least mean square loop for self-interference cancellation in in-band full-duplex OFDM systems," in Proceedings of 85th IEEE Vehicular Technology Conference (VTC Spring), Sydney, Australia, 2017, pp. 1-5.

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List of abbreviations

ADC Analog-to-Digital Converter

AGC Automatic Gain Control

ALMS Analog Least Mean Square

AP Access Point

BPF Bandpass Filter

CSI Channel State Information

CW Continuous Wave

DF Degradation Factor

DFT Discrete Fourier Transform

DSP Digital Signal Processing

FPGA Field Programmable Gate Array

GCW-SAR Generalized Continuous Wave Synthetic Aperture Radar

I/Q In-phase/ Quadrature

IBFD In-band Full-duplex

IC Integrated Circuits

ISR Interference suppression Ratio

ISRLB Interference suppression Ratio Lower Bound

LMS Least Mean Square

LO Local Oscillation

MIMO Multiple Input Multiple Output

ODE Ordinary Differential Equation

OFDM Orthogonal Frequency-Division Multiplexing

PA Power Amplifier

RC Resistor-Capacitor

RF Radio Frequecy

RRC Root-raised Cosine

Rx Receive

SAR Synthetic Aperture Radar

SI Self-Interference

SIC Self-Interference Cancellation

SISO Single Input Single Output

Tx Transmit

List of symbols

$\mathbf{A}$ The beamforming matrix

a_i The i-th complex data symbol

α Decay constant of the lowpass filter

$\mathbb{C}$ The complex set

h_l The l-tap of the modelled SI channel coefficient

$\mathbf{H}(l)$ The SI channel coefficient matrix in IBFD MIMO systems

$h(t)$ The real SI channel impulse response

$\mathbf{I}_M$ The identity matrix of order M

$\otimes$ The Kronecker product

L The total number of taps in the ALMS loop

$\mathbf{\Lambda}$ The diagonal matrix composed by eigenvalues of the autocorrelation matrix

λ_l The l-th eigenvalue of the autocorrelation matrix

μ The LNA gain

$n(t)$ The additive Gaussian noise

$P_{d_m}(t)$ The residual signal power at the m-th receiver chain

$\Phi(\tau)$ The autocorrelation funtion of transmitted signal

$\mathbf{\Phi}$ The autocorrelation matrix of transmitted signal

$p(t)$ Transmit pulse shaping filter

$\mathbf{Q}$ The orthonormal modal matrix composed by eigenvectors of the autocorrelation matrix

$s(t)$ The signal of interest

T_d The delay unit between two adjacent taps

T_s The transmitted symbol duration

$u_l(t)$ The weighting error function

V_X Root mean square amplitude of the transmitted signal

$x(t)$ Transmitted RF signal

$z(t)$ Self-interference RF signal

Abstract

Recently, In-band full-duplex (IBFD) transmission, which allows transceivers to transmit and receive simultaneously on a single frequency band, is regarded as a promising solution for the problem of frequency spectrum shortage. However, a fundamental challenge encountered in realizing IBFD communications is self-interference (SI), which is the strong interference imposed by the transmitter blocking its co-located receiver from the signal of interest. Therefore, to enable the IBFD mode, great efforts have been devoted to mitigate SI to beyond the noise floor level. Among various approaches proposed in the radio frequency (RF) domain, analog least mean square (ALMS) loop is a promising structure for SI cancellation (SIC) due to its simplicity and efficiency. However, the behaviours of the ALMS loop have not been fully understood and its application was proposed for single-carrier and single antenna IBFD communication systems only.

This study aims at tackling the problem of SI in the RF domain for various IBFD systems using the ALMS loop. The contributions of this thesis are as follows. Firstly, the performances of the ALMS loop with different transmitted signals is investigated. It shows that due to the cyclostationary effect of the transmitted signals, SI cannot be removed completely by the ALMS loop but there exists an irreducible SI. The lower bounds of this irreducible SI are derived for both single-carrier and multi-carrier IBFD systems. Additionally, it proves that the ALMS loop also performs well with deterministic signals in full-duplex synthetic aperture radars. Secondly, by characterizing the ALMS loop in the frequency domain, the achievable levels of SIC by the ALMS loop in both

analog and digital domains are revealed. Thirdly, the performance of the ALMS loop under hardware impairment conditions is investigated. More importantly, a degradation bound is found to determine how much of compensation should be obtained from other means of SI mitigation for a given level of imperfection. Fourthly, a novel beam-based analog SIC structure employing the ALMS loop is proposed for IBFD multiple input multiple output (MIMO) systems to significantly reduce the number of adaptive filters required for SIC in IBFD MIMO systems. Finally, a practical structure of the ALMS loop is proposed and a prototype is implemented using off-the-shelf components to provide experimental results confirming all the theoretical findings. The analyses and practical results in this thesis provide a comprehensive view of the ALMS loop and prove its potential application for SIC in different IBFD radios.