

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

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*Anh Tuyen Le*

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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*

Doctor of Philosophy  
*in*  
Engineering

*by*

**Anh Tuyen Le**

*to*

School of Electrical and Data Engineering  
Faculty of Engineering and IT  
University of Technology Sydney  
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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

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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)*, Auckland, New Zealand, Nov. 2019, pp. 1-5 (Best Student Paper Award)

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  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.

# TABLE OF CONTENTS

<b>List of Publications</b>	<b>iii</b>
<b>List of Figures</b>	<b>ix</b>
<b>List of Tables</b>	<b>xii</b>
<b>List of Abbreviations</b>	<b>xiii</b>
<b>List of Symbols</b>	<b>xv</b>
<b>Abstract</b>	<b>xvii</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Background . . . . .	1
1.1.1 In-Band Full-Duplex Operation . . . . .	1
1.1.2 Self-Interference . . . . .	2
1.2 Motivation and Contribution . . . . .	4
1.3 Thesis Outline . . . . .	7
<b>2 Literature Review</b>	<b>9</b>
2.1 Self-Interference Mitigation . . . . .	9
2.1.1 Propagation Domain Suppression . . . . .	9
2.1.2 Digital Self-Interference Cancellation . . . . .	11
2.1.3 Radio Frequency Domain Cancellation . . . . .	13
2.2 Least Mean Square Algorithm . . . . .	15
2.3 Analog Least Mean Square Loop . . . . .	17
<b>3 ALMS Loop with Different Signal Properties</b>	<b>21</b>
3.1 ALMS Loop for OFDM Systems . . . . .	21
3.1.1 OFDM System Model . . . . .	21

TABLE OF CONTENTS

---

3.1.2	Cyclostationary Analysis . . . . .	22
3.1.3	Simulation Results . . . . .	26
3.2	Single-Carrier and Multi-Carrier IBFD Systems . . . . .	27
3.2.1	Signal Models . . . . .	28
3.2.2	General Solution of Weighting Error Function . . . . .	30
3.2.3	Conclusion . . . . .	34
3.3	ALMS Loop with Deterministic Signal in FD SAR . . . . .	34
3.3.1	Introduction . . . . .	34
3.3.2	GCW-SAR Signal Model . . . . .	36
3.3.3	Stationary Analysis . . . . .	38
3.3.4	Simulation Results . . . . .	41
3.3.5	Conclusion . . . . .	43
<b>4</b>	<b>Frequency Domain Characterization and Performance Bounds of ALMS Loop</b>	<b>45</b>
4.1	Introduction . . . . .	45
4.2	Steady State Analysis of ALMS Loop . . . . .	46
4.2.1	Signal Models . . . . .	46
4.2.2	Steady State Analysis . . . . .	48
4.3	Frequency-Domain Analysis of Residual SI . . . . .	52
4.3.1	Eigen-Decomposition of Autocorrelation Matrices . . . . .	52
4.3.2	Frequency Domain Characterization of ALMS Loop . . . . .	54
4.3.3	Performance Lower Bounds . . . . .	55
4.4	Simulation Results . . . . .	58
4.5	Conclusion . . . . .	59
<b>5</b>	<b>ALMS Loop with IQ Imbalance</b>	<b>61</b>
5.1	Introduction . . . . .	61
5.2	System Architecture and Signal Models . . . . .	62
5.2.1	In-Band Full-Duplex Transceiver with ALMS Loop . . . . .	62
5.2.2	I/Q Imbalanced Signal Models . . . . .	64
5.3	Effects of I/Q Imbalance . . . . .	65
5.3.1	Impact on Loop Gain . . . . .	65
5.3.2	Impact on Cancellation Performance . . . . .	67
5.4	Simulation Results . . . . .	74
5.5	Conclusion . . . . .	77



<b>6</b>	<b>ALMS Loop for In-Band Full-Duplex MIMO Systems</b>	<b>79</b>
6.1	Introduction . . . . .	79
6.2	Principle of Beam-Based Analog SIC . . . . .	81
6.2.1	Beam-Based SIC . . . . .	81
6.2.2	ALMS Loop . . . . .	84
6.3	Stationary Analysis . . . . .	85
6.3.1	Cancellation Performance . . . . .	85
6.4	Reference Signals Generation . . . . .	90
6.4.1	Using Additional Transmit Chains . . . . .	90
6.4.2	Selecting from Transmitted Signals . . . . .	92
6.5	Conclusion . . . . .	98
<b>7</b>	<b>ALMS Loop - A Practical Perspective</b>	<b>99</b>
7.1	Introduction . . . . .	99
7.2	Related Works . . . . .	100
7.2.1	Analog Multi-Tap Adaptive Filters . . . . .	100
7.2.2	ALMS Loop . . . . .	102
7.3	Implementation of ALMS loop . . . . .	103
7.4	Measurement Results . . . . .	106
7.4.1	Measurement Setup . . . . .	106
7.4.2	Measurement Results . . . . .	107
7.5	Conclusion . . . . .	109
<b>8</b>	<b>Conclusion and Future Work</b>	<b>113</b>
8.1	Conclusion . . . . .	113
8.2	Future Work . . . . .	115
<b>A</b>	<b>Appendix</b>	<b>117</b>
A.1	Proof of Constant $E_h\{H(e^{j\omega_k})\}$ . . . . .	117
A.2	Derivation of $ISRLB_\alpha$ and $ISRLB_d$ . . . . .	117
A.2.1	$ISRLB_\alpha$ . . . . .	117
A.2.2	$ISRLB_d$ . . . . .	118
A.3	Derivation of Residual SI Power . . . . .	120
A.4	Solution of Steady-State Weighting Error Function . . . . .	121
A.5	Derivation of Modeling Error . . . . .	124
A.6	Derivation of Weighting Error Functions . . . . .	125

TABLE OF CONTENTS

---

**Bibliography**

**129**

## LIST OF FIGURES

FIGURE	Page
1.1 IBFD radio terminal. . . . .	3
1.2 SI components and the requirements of SIC. . . . .	3
1.3 Three steps of SIC. . . . .	4
1.4 Five researches problems. . . . .	5
2.1 Propagation domain passive approaches: (a) Physical separation; (b) Spatial separation; (c) Antiphase control; (d) Cross-polarization. . . . .	10
2.2 Amount of suppression by antenna separation at 2.45 GHz. . . . .	10
2.3 Digital cancellation using channel modelling methods . . . . .	12
2.4 RF domain SIC approaches: (a) Additional transmit chain; (b) Multi-tap adaptive filter. . . . .	13
2.5 Multi-tap filter SIC techniques: (a) Time-domain approaches; (b) Frequency-domain approaches. . . . .	14
2.6 One tap of a closed-loop multi-tap filter. . . . .	15
2.7 $L$ -tap transversal adaptive filter structure. . . . .	16
2.8 $L$ -tap transversal continuous-time adaptive filter structure. . . . .	17
2.9 ALMS loop structure. . . . .	19
2.10 Earlier research on ALMS loop. . . . .	20
3.1 $g(t, \tau)$ with $T_o = 80T_s$ and pulse shaping roll-off factor 0.25. . . . .	23
3.2 (a) Normalized weight error; and (b) Normalized weight error variation. . . . .	24
3.3 ISRLB versus $\alpha T_s$ with various windowing roll-off factors $\beta_o$ . . . . .	25
3.4 Simulated and theoretical weighting coefficients of ALMS loop with $T_s$ spacing. . . . .	27
3.5 Simulated and theoretical convergence curves for residual interference power of the ALMS loop with $T_s$ and $T_s/2$ spacing in the first scenario. . . . .	28
3.6 (a) Normalized weight error; and (b) Normalized weight error variation with the loop gain $\mu A^2 = 1000$ , $\alpha T_s = 0.003$ , $T_o = 80T_s$ , and $\beta_s = \beta_o = 0.25$ . . . . .	33
3.7 ISRLB of the two systems with various values of $\beta_s$ and $\beta_o$ . . . . .	34
3.8 The autocorrelation function of $P(t)$ with chirp rate $k_r = 2.5 \times 10^{12}$ . . . . .	39
3.9 The residual SI power in the first scenario for $T_d = 1/nB$ , with $n = 1, 2$ and $L = 4, 8$ , respectively. . . . .	42

3.10	The residual SI power in the second scenario for $T_d = 1/nB$ with $n = 1, 2$ , and $L = 4, 8$ , respectively. . . . .	43
4.1	The ALMS loop structure. . . . .	47
4.2	(a) Raised cosine spectrum; (b) $S_X(e^{j\omega})$ ; (c) $S_X(e^{j\omega_k})$ versus eigenvalues $\lambda_k$ , with $L = 256, A^2 = 100, \beta = 0.2, T_d = T_s/2, T_s = 1$ . . . . .	53
4.3	Frequency dependent attenuation factors with various values of $\beta, L = 256, A^2 = 100, T_d = T_s/2$ . . . . .	55
4.4	ISR lower bounds versus $\beta$ with $\alpha = 2000, 2200, \text{ and } 2500$ . . . . .	57
4.5	PSDs of the SI $Z(t)$ , residual SI $V(t)$ , and residual SI after the matched filter $\tilde{V}(t)$ with $\beta = 0.5, \mu A^2 = 1000, T_d = T_s/2$ , and $L = 8$ . . . . .	59
4.6	ISRs in the analog domain and digital domain versus $\beta$ with $\mu A^2 = 1000, T_d = T_s/2$ . . . . .	60
5.1	The ALMS loop structure. . . . .	63
5.2	The loop gain ratio versus amplitude. . . . .	67
5.3	The normalized autocorrelation function of the transmitted signals. . . . .	68
5.4	$\overline{DF}$ versus amplitude and phase errors with different $\beta$ for $L = 8$ and (a) $f_c = 2432$ MHz and (b) $f_c = 5200$ MHz. . . . .	71
5.5	$\overline{DF}$ versus amplitude and phase errors with different $L$ for $\beta = 0.25$ and (a) $f_c = 2432$ MHz and (b) $f_c = 5200$ MHz. . . . .	72
5.6	$DF$ versus amplitude and phase errors when $\beta = 0$ and $T_d = T_s$ . . . . .	75
5.7	The complex signals $x_1(t)$ and $x_2(t)$ with $\rho_1 = \rho_2 = 3$ dB, $\theta_1 = \theta_2 = 5^\circ$ . . . . .	76
5.8	Residual SI powers in single-carrier system with $\rho_1 = \rho_2 = 3$ dB, $\theta_1 = \theta_2 = 5^\circ$ and (a) $f_c = 2432$ MHz and (b) and $f_c = 5200$ MHz. . . . .	76
5.9	Residual SI powers in OFDM system with $\rho_1 = \rho_2 = 3$ dB, $\theta_1 = \theta_2 = 5^\circ$ and (a) $f_c = 2432$ MHz and (b) $f_c = 5200$ MHz. . . . .	77
6.1	Proposed beam-based analog SIC structure. . . . .	82
6.2	ALMS loop for beam-based cancellation structure. . . . .	84
6.3	Beam-based analog SIC with auxiliary transmit chains. . . . .	90
6.4	The averaged and converged interference suppression ratio. . . . .	91
6.5	Normalized SI and residual SI powers for (a) $8 \times 8$ IBFD MIMO systems and (b) 2 beams IBFD MIMO systems. . . . .	92
6.6	Proposed beam-based analog SIC structure. . . . .	93
6.7	Transformation from $\underline{\mathbf{h}}$ to $\bar{\underline{\mathbf{u}}}$ . . . . .	93

LIST OF FIGURES

---

6.8	(a) Geometric mean of $D_\Omega$ and (b) $ISR$ for all possible selections of $\mathbf{A}_r$ . . . . .	95
6.9	SI channel impulse response $h_{2,4}(t)$ (top) and modeled tap coefficients $h_{2,4}(l)$ (bottom) for (a) arbitrary and (b) $T_d$ spaced delay between multipaths. . . . .	96
6.10	Interference suppression ratio under (a) arbitrary delay interference channel and (b) $T_d$ spaced interference channel. . . . .	97
6.11	Interference suppression ratio with the worst reference signals. . . . .	97
7.1	Multi-tap adaptive filter structure. . . . .	101
7.2	Output spectra of (a) a multiplier or a modulator with an LPF and (b) an unfiltered modulator. . . . .	103
7.3	A practical structure of the ALMS loop. . . . .	104
7.4	Prototype of the ALMS loop and a part of the receiver. . . . .	105
7.5	The measurement setup. . . . .	107
7.6	Measurement results for 20 MHz bandwidth. . . . .	108
7.7	Measurement results for 50 MHz bandwidth. . . . .	109
7.8	Cancellation performances with different roll-off factors. . . . .	110
7.9	Cancellation performances with OFDM signal. . . . .	110

## LIST OF TABLES

<b>TABLE</b>	<b>Page</b>
6.1 Comparison with existing methods for IBFD MIMO . . . . .	98
7.1 Comparison of existing multi-tap adaptive filters . . . . .	101
7.2 Summary of publications on ALMS loops . . . . .	102

## 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

## LIST OF ABBREVIATIONS

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**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 Frequency

**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

$\alpha$  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

$\lambda_l$  The  $l$ -th eigenvalue of the autocorrelation matrix

$\mu$  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 function of transmitted signal

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

## LIST OF SYMBOLS

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$p(t)$  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.