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Signal Processing for Joint Communication and Radar Sensing Techniques in Autonomous Vehicular Networks

by

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Certificate of Authorship/Originality

I, Yuyue Luo declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Electrical and Data Engineering at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference 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.

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ABSTRACT

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Joint communication and radar (radio) sensing (JCAS, also known as Radar-Communications) technology is promising for autonomous vehicular networks, for its appealing capability of realizing communication and radar sensing functions in an integrated system. Millimeter wave (mmWave) band has great potential for JCAS, and such mmWave systems often require the use of steerable array radiation beams. Therefore, beamforming (BF) is becoming a demanding feature in JCAS. Multibeam technology enables the use of two or more subbeams in JCAS systems, to meet different requirements of beamwidth and pointing directions. Generating and optimizing multibeam subject to the requirements is critical and challenging, particularly for systems using analog arrays.

In this thesis, we investigate the BF techniques for JCAS, addressing the following two issues:

1. The multibeam generation and optimization for JCAS, considering both communication and sensing performance;

2. BF generation in the presence of hardware imperfections in mmWave JCAS systems, particularly those associated with quantized phase shifters, and the radiation characteristics of antenna arrays.

Regarding the first issue, we mainly study two classes of multibeam generation methods: 1) the optimal combination of two pre-generated subbeams, and their BF vectors, using a combining phase coefficient; 2) global optimization methods

which directly find solutions for a single BF vector. For the optimal combination problems, we firstly study the communication-focused optimization in two typical scenarios. We also develop constrained optimization problems, considering both the communication and sensing performances. Closed-form solutions for the optimal combination coefficient are provided in these works. We also formulate several global optimization problems and managed to provide near-optimal solutions to the original intractable complex NP-hard optimization problems, using semidefinite relaxation (SDR) techniques.

Towards the second issue, we firstly study the quantization of the BF weight vector with the use of phase shifters. We focus on the two-phase-shifter array, where two phase shifters are used to represent each BF weight. We propose novel joint quantization methods by combining the codebooks of the two phase shifters. Analytically, the mean squared quantization error (MSQE) is derived for various quantization methods. We also propose BF methods by embedding the active pattern of antennas in the robust BF algorithms: 1) the diagonal loading and 2) the worst-case performance optimization algorithms. With the use of a more accurate array model, these methods can significantly reduce performance degradation caused by inconsistency between hypothesized ideal array models and practical ones.

Dedication

To my parents Xianzhi Yu and Rui Luo.

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List of Publications

0.1 Publications Related to This Thesis

Journal Papers

J-1. **Y. Luo**, J. Andrew Zhang, X. Huang, W. Ni, and J. Pan, "Optimization and Quantization of Multibeam Beamforming Vector for Joint Communication and Radio Sensing," in *IEEE Trans. Commun.*, vol. 67, no. 9, pp. 6468-6482, 2019.

J-2. **Y. Luo**, J. Pan, J. A. Zhang, and S. Huang "Worst-Case Performance Optimization Beamformer with Embedded Array's Active Pattern," in *Int. J. of Antennas and Propagat.*, vol. 2018, Article ID 9237321.

J-3. **Y. Luo**, J. Andrew Zhang, X. Huang, W. Ni, and J. Pan, "Multibeam Optimization for Joint Communication and Radio Sensing Using Analog Antenna Arrays," submitted to *IEEE Trans. Veh. Technol.*.

Conference Papers

C-1. **Y. Luo**, J. A. Zhang, S. Huang, J. Pan, and X. Huang, "Quantization with Combined Codebook for Hybrid Array Using Two-Phase-Shifter Structure," *IEEE Int. Conf. on Commun. (ICC 2019)*, May 20-24, 2019.

C-2. **Y. Luo**, J. A. Zhang, W. Ni, J. Pan, and X. Huang, "Constrained Multibeam Optimization for Joint Communication and Radio Sensing," *IEEE Global Communi. Conf. (GLOBECOM 2019)*, Dec. 9-13, 2019.

C-3. **Y. Luo**, S. Huang, J. Pan, "A New Robust Beamforming Algorithm: Embedding Array's Active Pattern in Diagonal Loading Method," *IEEE Asia-Pac. Microwave Conf. (APMC 2017)*, Nov. 13-16, 2017.

0.2 Other Publications

J-4 S. Huang, P. Jin, **Y. Luo**, and Deqiang Yang, "Single-Source Surface Integral Equation Formulations for Characteristic Modes of Fully Dielectric-Coated Objects," in *IEEE Trans. Antennas Propagat.*, vol. 67, no. 7, pp. 4914 - 4919, 2019.

J-5 S. Huang, P. Jin, and **Y. Luo**, "Investigations of Non-Physical Characteristic Modes of Material Bodies," in *IEEE ACCESS*, pp: 17198-17204, Mar. 2018.

J-6 S. Huang, P. Jin, and **Y. Luo**, "Study on the Relationships between Eigenmodes, Natural Modes, and Characteristic Modes of Perfectly Electric Conducting Bodies," in *Int. J. of Antennas and Propagat.*, vol. 2018, Article ID 8735635.

J-7 Y. Wang, J. Hu, **Y. Luo**, "A Terahertz Tunable Waveguide Bandpass Filter Based on Bimorph Microactuators," in *IEEE Microwave Wireless Compon. Lett.*, vol. 29, no. 2, pp. 110 - 112, 2019.

J-8 B. Ma, P. Jin, E. Wang, and **Y. Luo**, "Conformal Bent Dielectric Resonator Antennas With Curving Ground Plane," in *IEEE Trans. Antennas Propagat.*, vol. 67(3), pp: 1931-1936, Mar. 2019.

J-9 B. Ma, P. Jin, E. Wang, and **Y. Luo**, "Fixing and Aligning Methods for Dielectric Resonator Antennas in K Band and Beyond," in *IEEE ACCESS*, pp: 12638-12646 , Jan. 2019.

Contents

List of Figures

Abbreviation

1-PS - One-Phase-Shifter

2-PS - Two-Phase-Shifter

AoA: Angle of Arrival

AoD: Angle of Departure

AP: Active Pattern

APDL: Active Pattern embedded Diagonal Loading

APWC: Active Pattern Worst-Case

AWGN: Additive White Gaussian Noise

BER - Bit Error Rate

BF - Beamforming

CRB - Cramér–Rao bound

CRPS - Communication Reception and Passive Sensing

CTAS - Communication Transmission and Active Sensing

DFCS - Dual-functional Communication and Radar Sensing

DL - Diagonal Loading

DoA - Direction of Arrival

DSRC - Dedicated Short Range Communication

DSSS - Direct Sequence Spread Spectrum

EC-R - Embedding Communication function in Radar waveform

ER-C - Embedding Radar function in Communication waveform

FBND - Fast Block Noncoherent Decoding

GLRT - Generalized Likelihood Ratio Test

GSM - Global System for Mobile Communications

ILS: Iterative Least Square

INR: Interference-to-Noise-Ratio

ISM: Industrial, Scientific and Medical

JCAS: Joint Communication and Radar Sensing

JCR: Joint Communication and Radar waveform design

LGSS: Improved Golden Section Search

LGSS-Q: Improved Golden Section Search-Quantization

LOS: Line-of-Sight

LT: Loss Tangent

LSMI: Loaded Sample Matrix Inversion

MFCW: Multiple Frequency Continuous Wave

MIMO: Multi input multi output

MSE - Mean Squared Error

MSQE - Mean Squared Quantization Error

NLOS: Non-Line-of-Sight

NP-hard: Non-deterministic Polynomial-time hard

OFDM - Orthogonal Frequency Division Multiplexing

PBR - Passive Bistatic Radar

PSK - Phase-shift Keying

QAM - Quadrature Amplitude Modulation

QCQP - Quadratically Constrained Quadratic Programs

RDP - Relative Dielectric Permittivity

RCC - Radar-communication Coexistence

RF - Radio Frequency

Rx - Receive

SDR - Semidefinite Relaxation

SDP - Semidefinite Programming

SINR - Signal-to-Interference-plus-Noise Ratio

SLL - Sidelobe Level

SNR - Signal-to-Noise Ratio

SMI - Sample Matrix Inversion

SVD: Singular value decomposition

TDD - Time Division Duplex

Tx - Transmit

ULA: Uniform Linear Array

V2V: Vehicle-to-vehicle

V2I: Vehicle-to-everything

V2P: Vehicle-to-pedestrian

V2X: Vehicle-to-everything

WAVE: Wireless Access in Vehicular Environments

WCRB: Worst-Case performance optimization Robust Beamformer

Nomenclature and Notation

Bold lower-case alphabets denote column vectors.

Bold Capital letters denote matrices.

$(\cdot)^H$, $(\cdot)^*$, $(\cdot)^T$, $(\cdot)^{-1}$, and $(\cdot)^\dagger$ denote the Hermitian transpose, conjugate, transpose, inverse, and pseudo-inverse, respectively.

$|\cdot|$ and $\|\cdot\|$ denote the element-wise absolute value and the Euclidean norm, respectively.

$E(\cdot)$ denotes the expected value.

$\arg(\cdot)$ denotes the argument of a complex number. $\arg\max$ and $\arg\min$ denote arguments of the maxima and the minimum, respectively.

$\mathfrak{Re}\{\cdot\}$ and $\mathfrak{Im}\{\cdot\}$ denote the real and imaginary part of a complex variable, respectively.

$\mathbb{R}^n$ and $\mathbb{S}^n$ denote the set of all real $n \times n$ matrices and real symmetric $n \times n$ matrices, respectively.