UNIVERSITY OF TECHNOLOGY SYDNEY
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Fast and Accurate Estimation of Angle-of-arrival in Millimetre-wave Large-scale Hybrid Arrays

by

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Certificate of Authorship/Originality

I, Kai Wu declare that this thesis, is submitted in fulfilment of the requirements for the award of doctor of philosophy, in the Faculty of Engineering and Information Technology 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. I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree except as fully acknowledged within the text. This thesis is the result of a research candidature jointly delivered with Xidian University as part of a Collaborative Doctoral Research Degree. This research is supported by the Australian Government Research Training Program.

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ABSTRACT

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Hybrid array is able to leverage array gains, transceiver sizes and costs for massive multiple-input-multiple-output (MIMO) systems in millimetre wave frequencies. Challenges arise from estimation of angle-of-arrival (AoA) in hybrid arrays, due to the array structure and the resultant estimation ambiguities and susceptibility to noises. In this thesis, we study the unambiguous and non-iterative AoA estimation in two types of hybrid arrays — Localized Hybrid Array of Phased SubArrays (LHA-PSAs) and Lens Antenna Arrays (LAAs). For each type, two AoA estimation approaches are proposed for narrowband and wideband, respectively. The main innovation of the approaches include:

- The deterministic sign rules and patterns in LHA-PSAs are unprecedentedly discovered, and exploited to eliminate the estimation ambiguities;
- The optimal trade-off between different error sources is achieved, minimising the wideband AoA estimation error in LHA-PSAs;
- A new wide beam synthesis method is developed for LAAs, which substantially improves the AoA estimation efficiency in LAAs;
- New spatial-frequency patterns are unveiled exploiting the spatial-wideband effect, leading to fast and accurate wideband AoA estimation in LAAs.

Performance analysis is provided for all the approaches with closed-form estimation (lower) bounds derived. Corroborated by simulations, our approaches are able to dramatically improve AoA estimation accuracy while reducing complexity and the number of training symbols, as compared to the state of the art. The estimation errors of our methods asymptotically approach the (lower) bounds.

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I would like to express my special thanks to Prof. Jay Guo, the founding Director of the Global Big Data Centre (GBDTC), University of Technology Sydney (UTS), for proposing the concept and developing the prototype of the hybrid array of phased subarrays, early in 2009. This hybrid array, along with the related studies carried out by Prof. Xiaojing Huang and Prof. Andrew Zhang from GBDTC, motivate the researches in Chapters 2 and 3. In later 2018, Prof. Guo generously shared the idea of reconfigurable multi-beam antennas, which motivates the work in Chapter 4 and some ongoing researches.

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Kai Wu

Sydney, Australia, 2019

List of Publications

Journal Papers

J-1 . **K. Wu, W. Ni, T. Su, R. P. Liu and Y. J. Guo**, *"Exploiting Spatial-Wideband Effect for Fast AoA Estimation at Lens Antenna Array,"* ***IEEE Journal of Selected Topics in Signal Processing***, accepted, 2019.

J-2 . **K. Wu, W. Ni, T. Su, R. P. Liu and Y. J. Guo**, *"Large-scale Hybrid Antenna Array for Millimeter-Wave/Terahertz High-Speed Railway Communication,"* ***IEEE Communications Magazine***, accepted, 2019.

J-3 . **K. Wu, W. Ni, T. Su, R. P. Liu and Y. J. Guo**, *"Expeditious Estimation of Angle-of-Arrival for Hybrid Butler Matrix Arrays,"* ***in IEEE Transaction on Wireless Communications (TWC)***, vol. 18, no. 4, pp. 2170-2185, April 2019.

J-4 . **Q. Li, T. Su and K. Wu**, *"Accurate DOA Estimation for Large-Scale Uniform Circular Array Using a Single Snapshot,"* ***IEEE Communications Letters***, vol. 23, no. 2, pp. 302-305, Feb. 2019.

J-5 . **K. Wu, W. Ni, T. Su, R. P. Liu and Y. J. Guo**, *"Efficient Angle-of-Arrival Estimation of Lens Antenna Arrays for Wireless Information and Power Transfer,"* ***in IEEE Journal on Selected Areas in Communications (JSAC)***, vol. 37, no. 2, pp. 116-130, Sep. 2018.

J-6 . **K. Wu, W. Ni, T. Su, R. P. Liu and Y. J. Guo**, *"Robust Unambiguous Estimation of Angle-of-Arrival in Hybrid Array With Localized Analog Subarrays,"* ***in IEEE TWC***, vol. 17, no. 5, pp. 2987-3002, May 2018.

J-7 . **K. Wu, W. Ni, T. Su, R. P. Liu and Y. J. Guo**, *"Fast and Accurate Estimation of Angle-of-Arrival for Satellite-Borne Wideband Communication System,"* ***in IEEE JSAC***, vol. 36, no. 2, pp. 314-326, Feb. 2018.

Contents

List of Figures

Abbreviation

Analog-to-Digital and Digital-to-Analog Converters (ADC/DAC)

Angle-of-Arrivals (AoAs)

Auxiliary Beam Pair (ABP)

Additive White Gaussian Noise (AWGN)

Base Stations (BSs)

Cyclic Prefix (CP)

Cramér-Rao Lower Bound (CRLB)

Coherent Signal-subspace Method (CSM)

Designs-of-Freedom (DoF)

Discrete Antenna Arrays (DAAs)

Discrete Fourier Transform (DFT)

Differential DFT Beams (DDBs)

Differential Beam Search (DBS)

Double Cross-Correlation (DCC)

DFT Beam Differences (DBDs)

Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT)

fifth-Generation (5G)

Gigabits per second (Gbps)

Geosynchronous Earth Orbit (GEO)

High-Speed Railway (HSR)

High-Speed Trains (HSTs)

Inverse DFT (IDFT)

Incoherent Signal sub-space Method (ISM)

Lens Antenna Arrays (LAAs)

Localized Hybrid Array of Phased SubArrays (LHA-PSA)

Low Earth Orbit (LEO)

Line-of-Sight (LoS)

Least Squared (LS)

Multiple-Input-Multiple-Output (MIMO)

MUltiple SIgnal Classification (MUSIC)

Mean Square Error (MSE)

MSE Lower Bound (MSELB)

millimetre-Wave (mmWave)

Non-Line-of-Sight (NLoS)

Orthogonal Frequency-Division Multiplexing (OFDM)

Parallel Interference Cancellation (PIC)

Right-Hand Side (RHS)

Radio Frequency (RF)

Signal-to-Noise Ratio (SNR)

Successive Interference Cancellation (SIC)

Singular Value Decomposition (SVD)

Simultaneous WIPT (SWIPT)

Wireless Information and Power Transfer (WIPT)

Wireless Power Transfer (WPT)

Wireless Information Transfer (WIT)