Parameter Estimation and Hybrid Precoding Design for Millimeter Wave Mobile Networks

by

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Doctor of Philosophy

under the supervision of

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Certificate of Original Authorship

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, *Zhitong Ni,* 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, Faculty of Engineering and IT* at the University of Technology Sydney.

This thesis 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.

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ABSTRACT

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With the exponential rise of mobile data rates, millimeter wave (mmWave) mobile networks (mmWMNs) have become the trend in the 5th generation mobile cellular networks and beyond. In mmWMNs, the mmWave band can provide the ultra-high data rates due to its extremely wide frequency band resources, and the densely deployed base stations (BS) can significantly improve the network throughput per cell. However, the severe path loss and fading issues of the mmWave band dramatically impair the received signal-to-interference-plus-noise ratio and limit the network throughput. A revolution in the hardware architecture and the signal processing has been occurring for years. Numerous novel channel estimation and precoding techniques were proposed. In particular, angular sparsity is an intensified property for conducting mmWave channel estimations and hybrid precoding is a promising technique to realize mmWave communications. Existing hybrid precoding schemes either require full channel state information (CSI) or use codebook-based design. The former one requires highly accurate estimated channels while the latter has a degraded system performance. On the other hand, mmWave radar sensing has been successfully and commercially adopted for decades. With the number of electric devices increasing rapidly, there exist more and more demands to fuse the radar functions into the mmWave communication mobile networks. The primary issue is to realize a robust mmWave communication system. Issues following this include how to jointly estimate the communication channel and the radar channel, and how to address the interferences between radar waveforms and communication waveforms.

Under this background, this doctoral thesis mainly focuses on signal processing techniques that can realize mmWave channel estimation for both radar and communication purposes, and hybrid beamforming/precoding algorithms that can increase the communication data rates. This thesis will include: 1) Subarray-based angle-of-arrivals (AoAs) estimation, where the AoAs can refer to both the line-of-sight (LOS) angles coming from users and the non-line-of-sight (NLOS) angles coming from targets; 2) Energy-efficient hybrid precoding and sparse precoding (virtual array), where both fully-connected and partially-connected hybrid precoders are optimized based on the metric of energy efficiency; 3) Adaptive hybrid precoding and the quantization of radio-frequency (RF) precoder using minimum subspace distortion (MSD), where the adaptive precoding aims to adjust the precoding matrix based on the transmit power, and the MSD quantization aims to improve the system performance loss caused by the quantization; 4) Uplink radar sensing fused in mmWMNs, where a radar sensing scheme is proposed without requiring synchronization between BS and user equipment.

Dedication

To my beloved family:

During conquering my Ph. D. period, my family give me a lot of supports mentally and financially. Without their supports, I would not live so happily and focus on my study and researches. As I lived in a small city when I was young, people there would not take study so serious. Many people finished their nine-year compulsory education and went to work. Fortunately, I outstood my study capability at that time. My family decided to let me continue my education from high school to university. I was lucky to get the opportunity to study abroad in Australia with the help of my supervisor, Dr. Andrew. Before I came here, my family helped me prepare my ID, supported me to join in a cram study session to improve my English, and gave me allowance monthly for my living. After I came here, I was always alone and couldn't find friends. My family talked with me frequently to make sure everything was fine. Even though Ph. D. has a stipend, I still have worries about my future and keep wondering that if I can support myself and live independently. My family also think that study is like an adventure that has so many uncertainties. Until now, I become relatively positive about my future. Now, I am about to finish my journey of Ph. D. and hope to find a decent job. I would like to thank those who support me to keep studying for this long time of period.

Sincerely,

Zhitong Ni.

Acknowledgements

I pursue my Ph.D. degree from 2017 in School of Information and Electronics, Beijing Institute of Technology, China, and get the opportunity to pursue a dual Ph. D. degree from 2019 in the School of Electrical and Data Engineering, Faculty of Engineering and IT, the University of Technology Sydney (UTS), Australia.

Back in China, I was well nurtured by many good professors, including Jianping An, Kai Yang, and Fei Gao, etc. They helped me acquire the basic expertise so that I can transfer smoothly from undergraduate to Ph. D. candidate. In 2018, I met Dr. Andrew Zhang fortunately who later invited me to study abroad and became my primary supervisor in Australia. I would deeply appreciate his hard work and academic perspective that helped me so much to go on my researches and produce publications. Whenever I have confusion about an academic problem, he can always help me overcome the obstacles. I also thank him for his kindness and recognition of giving me the chance to study abroad. In UTS, I learned many novel ideas from my colleagues and supervisors. The most important thing is that almost all my research publications are born when I study abroad. This could be a coincidence but I could not obtain so many outcomes without the help of Prof. Zhang and other colleagues. I would also thank my Associate supervisor, Dr. Xiaojing Huang, who also helped me a lot with my English writing.

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List of Publications

Journal Papers

J-1. Z. Ni, J. A. Zhang, K. Yang, F. Gao and J. An, "Estimation of Multiple Angle-of-Arrivals With Localized Hybrid Subarrays for Millimeter Wave Systems," in IEEE Transactions on Communications, vol. 68, no. 3, pp. 1897-1910, Mar. 2020.

J-2. Z. Ni, J. A. Zhang, K. Yang, F. Gao and J. An, "Low-Complexity Subarray-Based RF Precoding for Wideband Multiuser Millimeter Wave Systems," in IEEE Transactions on Vehicular Technology, vol. 69, no. 7, pp. 8028-8033, Jul. 2020.

J-3. Z. Ni, J. A. Zhang, K. Yang, F. Gao and J. An, " Hybrid Precoder Design with Minimum-Subspace-Distortion Quantization in Multiuser MmWave Communications," in IEEE Transactions on Vehicular Technology, pp. 11055-11065, Oct. 2020.

J-4. Z. Ni, J. A. Zhang, X. Huang, K. Yang and J. Yuan, "Uplink Sensing in Perceptive Mobile Networks With Asynchronous Transceivers," in IEEE Transactions on Signal Processing, vol. 69, pp. 1287-1300, Feb. 2021.

Conference Papers

C-1. Z. Ni, J. A. Zhang, K. Yang, F. Gao and Z. Gao, "Codebook Based Minimum Subspace Distortion Hybrid Precoding for Millimeter Wave Systems," 2018 IEEE Globecom Workshops (GC Wkshps), Abu Dhabi, United Arab Emirates, 2018, pp. 1-6.

C-2. Z. Ni, J. A. Zhang, X. Huang, K. Yang and F. Gao, "Parameter Estimation and Signal Optimization for Joint Communication and Radar Sensing," 2020 IEEE

International Conference on Communications Workshops (ICC Workshops), Dublin, Ireland, 2020, pp. 1-6.

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List of Figures

Abbreviation

5G NR - the fifth-generation New Radio

6G - the sixth-generation

AoA - Angle of Arrival

AoD - Angle of Departure

AWGN - Additive White Gaussian Noise

B5G - Beyond the fifth-generation

BF - Beamforming

BPD - Break-point Distance

BS - Base Station

CACC - Cross-antenna Cross Correlation

CFO - Carrier Frequency Offset

CP - Cyclic Prefix

CRB - Cramér-Rao bound

CS - Compressive Sensing

CSIT - Channel State Information at Transmitter

DAC - Digital-to-analog Converter

DC - Dynamic-combined

DFT - Discrete Fourier Transform

EE - Energy Efficiency

FC - Fully-connected

FS - Fixed Subarray

FFT - Fast Fourier Transform

GHz - Gigahertz

IoV - Internet of Vehicle

JRC - Joint Radar and Communication

LOS - Line-of-Sight

LSF - Large Scale Fading

LTE - Long Term Evolution

MIMO - Multi-input Multi-output

MMSE - Minimum Mean Squared Error

MmWMN - Millimeter Wave Mobile Network

MSD - Minimum Subspace Distortion

MU - Mobile User

MUI - Multiuser Interference

NLOS - Non-Line-of-Sight

OFDM - Orthogonal Frequency Division Multiplexing

PSK - Phase-shift Keying

RF - Radio Frequency

Rx - Receive

SDMA - Spatial Division Multiple Access

SE - Spectral Efficiency

SINR - Signal-to-interference-plus-noise Ratio

SNR - Signal-to-noise Ratio

SSF - Small Scale Fading

SVD - Singular Value Decomposition

THz - Terahertz

Tx - Transmit

TO - Timing Offset

UE - User Equipment

ULA - Uniform Linear Array

UPA - Uniform Planar Array

V2X - Vehicle-to-everything

WLAN - Wireless Local Area Network

Nomenclature and Notation

Notations:

Bold lower-case letters denote column vectors.

Bold upper-case letters denote matrices.

Italic Greek letters and alphabets denote scalars.

j denotes $\sqrt{-1}$.

$\mathbf{I}$ denotes the identity matrix.

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

$\|\cdot\|$ and $\|\cdot\|_F$ denote the Euclidean norm and Frobenius norm, respectively.

$|a|$ is the absolute value of a and $|\mathbf{A}|$ is the determinant of $\mathbf{A}$.

$[\mathbf{A}]_{m,n}$ is the (m, n)th entry of $\mathbf{A}$ and $[\mathbf{A}]_n$ is the nth column of $\mathbf{A}$.

$\angle(\cdot)$ denotes the phase value of a complex scalar, vector, or matrix.

$\mathbb{E}(\cdot)$ denotes the expected value.

$\mathrm{diag}(a_1, a_2, \cdots, a_X)$ is a function to form the entries or the matrices into a diagonal matrix, and $\mathrm{diag}(\mathbf{A})$ is a function to form the diagonal entries of $\mathbf{A}$ into a vector.

$\odot$ is Hadamard product. $\otimes$ is Kronecker product.

Common Symbols:

P	power
λ	wavelength
σ^2	variance of noise
f_{D}	Doppler frequency
f_c	carrier frequncy
$\mathbf{s}$	baseband symbols
$\mathbf{F}_{\mathrm{BB}}$	baseband precoder
$\mathbf{F}_{\mathrm{RF}}$	RF precoder
$\mathbf{x}$	transmitted signals
N_{T}	number of transmit antennas
N_{R}	number of receive antennas
N_{P}	number of RF chains
$\mathbf{H}$	channel matrix
L	number of paths
$\mathbf{W}$	BS combiner
$\mathbf{w}$	UE combiner
K	number of subcarriers
T	time period
Ω	equivalent angles
τ	time delays