

Hybrid Beamforming Systems with IQ Imbalance: Compensation and Performance Analysis

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
JULY 2022

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Hybrid Beamforming Systems with IQ Imbalance: Compensation and Performance Analysis

by

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Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2022

Dedicated to

My Grandparents

Late Shri Vishun Narayan Mahendra

and

Late Smt. Omvati Mahendra

Certificate

This is to certify that the thesis entitled “**Hybrid Beamforming Systems with IQ Imbalance: Compensation and Performance Analysis**” being submitted by **Rachit Mahendra** to the Department of Electrical Engineering, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is the record of the bona-fide research work carried out by him under our supervision. In our opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree. The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.



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Acknowledgements

First and foremost, I would like to express my sincere gratitude to my supervisors, **Prof. Saif Khan Mohammed** and **Prof. Ranjan K. Mallik**, for their invaluable advice and continuous support throughout my doctoral study. Their immense knowledge, rich experience, and helpful behavior have been a constant source of inspiration and the driving force for my doctoral research. Their trust in my proposed solutions has helped me to evolve as an independent researcher, and their constructive remarks have improved the quality and presentation of the research work. I consider myself fortunate to work under the guidance of these eminent faculties.

I would also like to thank my student research committee members Prof. Brijesh Lall, Prof. Seshan Srirangarajan, and Prof. S. Dharmaraja, for their valuable feedback and suggestions. I am grateful to Prof. S. D. Joshi and Prof. Surendra Prasad for their amazing teachings and motivational words. I am also thankful to Prof. Shankar Prakriya for providing workspace in the DSP Lab during the initial years of my doctoral research. I thank my institute, IIT Delhi, for financially supporting me through scholarships during my doctoral research. Thanks are also due to the non-teaching (office, laboratory, housekeeping, and security) staff at IIT Delhi for their direct and indirect contributions in making my journey smoother.

I would also like to extend my heartfelt thanks to my fellow researchers and friends at IIT Delhi, especially Dr. Sandeep Joshi, Dr. Alok Kumar Sinha, Dr. Brijesh Chander Pandey, Kamal Biswas, Sonali Garg, and Dr. Sasi Vinay Pechetti for their help and support, and also for making this journey a memorable one which I will always cherish. Many thanks to all my other friends for their friendship, help, and support.

This journey was impossible without the unconditional love, support, and blessings

of my family. I will always be thankful to my parents Shri Dinesh Kumar Mahendra and Smt. Veena Mahendra for everything, which words can't describe. I would also like to thank my brother Mohit Mahendra for his love and support.

Last but not the least, I would like to offer my sincere thanks to all who supported me through the thick and thin of my life.

Rachit Mahendra

Abstract

To cater to the ever increasing demand of high throughput, future wireless networks must be designed to provide orders of magnitude increased data rates as compared to contemporary wireless networks. Massive multiple-input multiple-output (MIMO) systems, which are equipped with a large number of antennas, can provide significantly increased throughput and have gained significant research interest in the last decade. For practical implementation of a massive MIMO system, the most efficient architecture in terms of cost and energy is the hybrid beamforming system (HBFS) in which a small number of radio-frequency chains are connected to a large antenna array through an analog network. The cost of a massive MIMO HBFS can further be reduced by using inexpensive components, which however are less precise and result in several types of hardware imperfections. In-phase and quadrature-phase imbalance or IQ imbalance (IQI) is one such hardware impairment. In this thesis, we study the performance of the point-to-point and multi-user (MU) HBFSs in the presence of IQI and we propose novel IQI compensation algorithms for the corresponding HBFSs.

Firstly, we focus on HBFSs affected by only transmitter IQI (Tx-IQI). For a Tx-IQI impaired point-to-point mm-wave HBFS, we study the impact of Tx-IQI on the achievable rate and we propose an algorithm to estimate the channel and Tx-IQI parameters. We also propose a Tx-IQI pre-compensation algorithm which is implemented at the transmitter and perfectly mitigate the effects of Tx-IQI in a point-to-point HBFS. Next, we consider the uplink (UL) of a Tx-IQI impaired MU-HBFS and it is shown that uncompensated Tx-IQI causes a finite ceiling of the UL achievable sum-rate at high signal-to-noise-ratio (SNR). Therefore, we propose a zero-forcing (ZF) based Tx-IQI compensation algorithm and provide the sum-rate analysis with the proposed Tx-IQI compensation. Through simulations, it is shown that the proposed Tx-IQI compensa-

tion algorithm effectively mitigates the undesired effects of both amplitude and phase mismatch even when different channel models are assumed. Thereafter, we have incorporated the effect of imperfect estimates and propose an algorithm to estimate the true channel coefficients and the user equipment (UE)'s Tx-IQI parameters at the base station (BS). We modify the Tx-IQI compensation algorithm for the imperfect channel state information (CSI) scenario and evaluate the sum-rate performance numerically. It is shown that with imperfect CSI, uncompensated Tx-IQI causes a finite ceiling of the UL sum-rate at high SNR, whereas there is no ceiling of the UL sum-rate with the proposed Tx-IQI compensation. However, inaccuracy in the estimated Tx-IQI parameters causes a performance gap between the sum-rates of an IQI-free system and that with the proposed Tx-IQI compensation.

We next focus on HBFSs affected by only receiver IQI (Rx-IQI). For an Rx-IQI impaired point-to-point mm-wave HBFS, we propose a method to estimate the channel and Rx-IQI parameters. We also propose an Rx-IQI compensation algorithm which is implemented at the receiver and perfectly alleviate the effects of Rx-IQI in a point-to-point HBFS. Next, we consider the downlink (DL) of an Rx-IQI impaired MU-HBFS for which we propose an Rx-IQI pre-compensation algorithm to be implemented at the BS and derive the closed-form DL sum-rate expressions for the ZF hybrid precoder. Through simulations, it is verified that the proposed Rx-IQI pre-compensation algorithm almost achieves the performance of an IQI-free HBFS, whereas uncompensated Rx-IQI causes a finite ceiling of the DL achievable sum-rate at high SNR. Thereafter, we consider the effect of imperfect estimates and propose an algorithm to estimate the channel coefficients and the UE's Rx-IQI parameters at the BS. We also modify the Rx-IQI pre-compensation algorithm for the imperfect CSI scenario and evaluate the sum-rate performance of the considered DL MU-HBFS numerically. It is shown that with imperfect CSI, uncompensated Rx-IQI causes a finite ceiling of the DL achievable sum-rate at high SNR, whereas there is no ceiling of the achievable sum-rate in the Rx-IQI pre-compensated HBFS. However, the error in the estimation of Rx-IQI parameters results in a performance gap between the sum-rates of an IQI-free system and that of a HBFS with the proposed Rx-IQI pre-compensation.

सार

उच्च थ्रूपुट की लगातार बढ़ती हुई मांग को पूरा करने के लिए भविष्य के वायरलेस नेटवर्क्स की रचना इस प्रकार की जानी चाहिए ताकि वह समकालीन वायरलेस नेटवर्क्स की तुलना में कई गुना डाटा रेट्स प्रदान कर सकें। विशाल मल्टीपल-इनपुट मल्टीपल-आउटपुट (एमआईएमओ) सिस्टम्स बड़ी संख्या में एंटेना से लैस होने के कारण उच्च थ्रूपुट प्रदान करने में सक्षम हैं और पिछले एक दशक में इस विषय पर काफी शोध हुआ है। लागत और ऊर्जा के संदर्भ में एक विशाल एमआईएमओ सिस्टम के व्यावहारिक कार्यान्वयन के लिए हाइब्रिड बीमफॉर्मिंग सिस्टम (एचबीएफएस) सबसे दक्ष आर्किटेक्चर है, जो एनालॉग नेटवर्क के माध्यम से रेडियो फ्रीक्वेंसी श्रृंखलाओं को एक बड़े एंटीना व्यूह से जोड़ता है। कम लागत वाले पुर्जों के उपयोग से विशाल एमआईएमओ एचबीएफएस की लागत को और कम किया जा सकता है, जो कम सटीक होते हैं और कई प्रकार की हार्डवेयर खामियां उत्पन्न करते हैं। इन-फेज और क्वाड्रेचर-फेज असंतुलन या आईक्यू असंतुलन (आईक्यूआई) ऐसी ही एक हार्डवेयर खामी है। हम इस थीसिस में आईक्यूआई की उपस्थिति में पॉइंट-टू-पॉइंट और मल्टी-यूज़र (एमयू) एचबीएफएस के प्रदर्शन का अध्ययन करते हैं और संबंधित एचबीएफएस के लिए आईक्यूआई क्षतिपूर्ति विधियां प्रस्तावित करते हैं।

सबसे पहले हम ट्रांसमीटर आईक्यूआई (टीएक्स-आईक्यूआई) से प्रभावित एचबीएफएस पर ध्यान केंद्रित करते हैं। एक टीएक्स-आईक्यूआई असंतुलित पॉइंट-टू-पॉइंट एमएम वेव एचबीएफएस के लिए हम अचीवेबल रेट पर टीएक्स-आईक्यूआई के प्रभाव का अध्ययन करते हैं तथा चैनल और टीएक्स-आईक्यूआई मापदंडों का अनुमान लगाने के लिए एक विधि प्रस्तावित करते हैं। हम एक टीएक्स-आईक्यूआई पूर्व क्षतिपूर्ति विधि भी प्रस्तावित करते हैं, जो कि ट्रांसमीटर पर कार्यान्वित की जाती है और एक पॉइंट-टू-पॉइंट एचबीएफएस में टीएक्स-आईक्यूआई के प्रभावों को पूर्ण रूप से खत्म करती है। इसके बाद हम एक टीएक्स-आईक्यूआई असंतुलित एमयू एचबीएफएस के अपलिंक (युएल) पर ध्यान केंद्रित करते हैं और यह सिद्ध करते हैं कि अक्षतिपूरित टीएक्स-आईक्यूआई उच्च सिग्नल-टू-नॉइस-रेश्यो (एसएनआर) परिदृश्य में अचीवेबल सम-रेट को सीमित करता है। इसलिए हम जीरो-फोर्सिंग (जेडएफ) पर आधारित एक टीएक्स-आईक्यूआई क्षतिपूर्ति विधि प्रस्तावित करते हैं और उसके सम-रेट का विश्लेषण करते हैं। सिमुलेशन के माध्यम से यह सिद्ध किया गया है कि प्रस्तावित टीएक्स-आईक्यूआई क्षतिपूर्ति विधि विभिन्न चैनल मॉडलों में भी एम्प्लीट्यूड और फेज असंतुलन के अवांछित प्रभावों को काफी कम करती है। इसके बाद हमने त्रुटिपूर्ण अनुमानों के प्रभाव को शामिल किया है और बेस स्टेशन (बीएस) पर सही चैनल गुणांकों तथा

उपयोगकर्ता उपकरण (यूई) के टीएक्स-आईक्यूआई मापदंडों का अनुमान लगाने के लिए एक विधि प्रस्तावित की है। हमने त्रुटिपूर्ण चैनल स्थिति (सीएसआई) परिदृश्य के लिए टीएक्स-आईक्यूआई क्षतिपूर्ति विधि को संशोधित किया है और सम-रेट प्रदर्शन का सिमुलेशन के माध्यम से मूल्यांकन किया है। यह सिद्ध किया गया है कि त्रुटिपूर्ण सीएसआई एवं उच्च एसएनआर परिदृश्य में अक्षतिपूरित टीएक्स-आईक्यूआई युएल सम-रेट को सीमित करता है, जबकि प्रस्तावित टीएक्स-आईक्यूआई क्षतिपूर्ति विधि के उपयोग के बाद युएल सम-रेट असीमित रूप से बढ़ता रहता है। हालांकि, अनुमानित टीएक्स-आईक्यूआई मापदंडों में शामिल त्रुटियों के कारण आईक्यूआई-मुक्त सिस्टम के सम-रेट और प्रस्तावित टीएक्स-आईक्यूआई क्षतिपूर्ति विधि के उपयोग वाले सिस्टम के सम-रेट के प्रदर्शन में अंतर पाया गया है।

इसके बाद हम केवल रिसीवर आईक्यूआई (आरएक्स-आईक्यूआई) से प्रभावित एचबीएफएस पर ध्यान केंद्रित करते हैं। एक आरएक्स-आईक्यूआई असंतुलित पॉइंट-टू-पॉइंट एमएम वेव एचबीएफएस के लिए हम चैनल और आरएक्स-आईक्यूआई मापदंडों का अनुमान लगाने वाली एक विधि प्रस्तावित करते हैं। हम एक आरएक्स-आईक्यूआई पूर्व क्षतिपूर्ति विधि भी प्रस्तावित करते हैं जो रिसीवर पर कार्यान्वित की जाती है और एक पॉइंट-टू-पॉइंट एचबीएफएस में आरएक्स-आईक्यूआई के प्रभावों को पूर्ण रूप से खत्म करती है। इसके बाद हम एक आरएक्स-आईक्यूआई असंतुलित एमयु एचबीएफएस के डाउनलिंक (डीएल) पर ध्यान केंद्रित करते हैं, जिसके लिए हम बीएस पर कार्यान्वित की जाने वाली एक आरएक्स-आईक्यूआई पूर्व क्षतिपूर्ति विधि प्रस्तावित करते हैं और जेडएफ हाइब्रिड प्रीकोडर के लिए क्लोज्ड-फॉर्म डीएल सम-रेट एक्सप्रेसन की खोज करते हैं। सिमुलेशन के माध्यम से यह सिद्ध किया गया है कि प्रस्तावित आरएक्स-आईक्यूआई पूर्व क्षतिपूर्ति विधि से लगभग आईक्यूआई-मुक्त सिस्टम का प्रदर्शन प्राप्त किया जा सकता है, जबकि अक्षतिपूरित आरएक्स-आईक्यूआई उच्च एसएनआर परिदृश्य में डीएल अचीवबल सम-रेट को सीमित करता है। इसके बाद हमने त्रुटिपूर्ण अनुमानों के प्रभाव को शामिल किया है और बेस स्टेशन (बीएस) पर सही चैनल गुणांकों तथा उपयोगकर्ता उपकरण (यूई) के आरएक्स-आईक्यूआई मापदंडों का अनुमान लगाने के लिए एक विधि प्रस्तावित की है। हमने त्रुटिपूर्ण सीएसआई परिदृश्य के लिए आरएक्स-आईक्यूआई पूर्व-क्षतिपूर्ति विधि संशोधित की है और डीएल एमयु-एचबीएफएस के सम-रेट प्रदर्शन का सिमुलेशन के माध्यम से मूल्यांकन किया है। यह सिद्ध किया गया है कि त्रुटिपूर्ण सीएसआई एवं उच्च एसएनआर परिदृश्य में अक्षतिपूरित आरएक्स-आईक्यूआई डीएल अचीवबल सम-रेट को सीमित करता है, जबकि प्रस्तावित आरएक्स-आईक्यूआई क्षतिपूर्ति विधि के उपयोग के बाद डीएल अचीवबल सम-रेट असीमित रूप से बढ़ता रहता है। हालांकि, अनुमानित आरएक्स-आईक्यूआई मापदंडों में शामिल त्रुटियों के कारण आईक्यूआई-मुक्त सिस्टम के सम-रेट और प्रस्तावित आरएक्स-आईक्यूआई क्षतिपूर्ति तकनीक के उपयोग वाले सिस्टम के सम-रेट के प्रदर्शन में अंतर पाया गया है।

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Abbreviations

ABFS	Analog beamforming system
ADC	Analog-to-digital converter
AoA	Angle of arrival
AoD	Angle of departure
AR	Augmented reality
AWGN	Additive white Gaussian noise
BER	Bit error rate
BS	Base station
CFO	Carrier frequency offset
CSI	Channel state information
DAC	Digital-to-analog converter
DBFS	Digital beamforming system
DL	Downlink
DoF	Degrees of freedom
EE	Energy efficiency
HBFS	Hybrid beamforming system
i.i.d.	Independent and identically distributed
IC	Integrated circuit
ICI	Inter-carrier interference
IF	Intermediate frequency
IoT	Internet of Things
IQ	In-phase and Quadrature-phase
IQI	IQ imbalance

LMMSE	Linear minimum mean square error
LNA	Low noise amplifier
LO	Local oscillator
LPF	Low pass filter
LS	Least Squares
LS-MIMO	Large scale MIMO
MIMO	Multiple-input multiple-output
mm-wave	Millimeter-wave
MMSE	Minimum mean square error
MRC	Maximal-ratio combining
MRT	Maximal-ratio transmission
MSE	Mean-squared error
MU	Multi user
MUI	Multi user interference
OFDM	Orthogonal frequency division multiplexing
OMP	Orthogonal matching pursuit
PA	Power amplifier
PN	Oscillator phase noise
PS	Phase shifter
QAM	Quadrature amplitude modulation
QoS	Quality of service
RF	Radio frequency
SCNs	Small cell networks
SE	Spectral efficiency
SEP	Symbol error probability
SINR	Signal-to-interference-and-noise-ratio
SISO	Single-input single-output
SNR	Signal-to-noise-ratio
SVD	Singular value decomposition

SWN	Switching network
TDD	Time-division duplexed
UE	User-equipment
UL	Uplink
UPA	Uniform planar arrays
URLLC	Ultra-reliable and low latency communication
VPS	Variable phase shifter
VPSN	VPS network
WL	Widely-linear
WL-MMSE	WL minimum mean square error
ZF	Zero forcing
ZMCSCG	Zero-mean circularly-symmetric complex Gaussian

Notations

\mathbb{C}	Set of complex numbers
\mathbb{R}	Set of real numbers
\mathbb{R}^+	Set of positive real numbers
\mathbb{Z}^+	Set of positive integers
j	Imaginary unit ($\sqrt{-1}$)
Uppercase/lowercase letters	Real/complex-valued scalars
Boldfaced lowercase letters	Real/complex-valued vectors
Boldfaced uppercase letters	Real/complex-valued matrices
$ \cdot $	Absolute part
\angle	Angle part
$\Re\{\cdot\}$	Real part
$\Im\{\cdot\}$	Imaginary part
$[\mathbf{a}]_m$	$(m, n)^{th}$ element of the vector \mathbf{a}
$[\mathbf{A}]_{m,n}$	$(m, n)^{th}$ element of the matrix \mathbf{A}
$\mathbf{A}_{1:K}$ or $[\mathbf{A}]_{:, (1:K)}$	Sub-matrix consisting of first K columns of \mathbf{A}
$[\mathbf{A}]_{(1:K), :}$	Sub-matrix consisting of first K rows of \mathbf{A}
$\mathbf{A}^{1/2}$	Matrix whose square is \mathbf{A}
$\mathbf{0}_{M \times N}$	Zero matrix of order $M \times N$
$\mathbf{1}_{M \times N}$	Ones matrix of order $M \times N$
\mathbf{I}_M	Identity matrix of order M
$\text{diag}(\cdot)$	Diagonal matrix
$\text{blk-diag}(\cdot)$	Block-diagonal matrix
$\det(\cdot)$	Determinant of a square matrix

$\ \cdot\ _1$	$\mathcal{L}1$ norm of a vector
$\ \cdot\ _2$	$\mathcal{L}2$ norm of a vector
$\ \cdot\ _F$	Frobenius norm of a matrix
\otimes	Kronecker product
\circ	Khatri-Rao product
$\text{vec}(\cdot)$	Vectorization operator
$\text{vec}^{-1}(\cdot)$	Inverse vectorization operator
$\mathbb{E}[\cdot]$	Expectation operator
$\text{Tr}(\cdot)$	Trace operator
$(\cdot)^*$	Conjugate operator
$(\cdot)^T$	Transpose operator
$(\cdot)^H$	Conjugate-transpose operator
$(\cdot)^{-1}$	Inverse operator
$(\cdot)^{-*}$	Conjugate-inverse operator
$(\cdot)^{-H}$	Conjugate-transpose-inverse operator
$\mathcal{CN}(a, b)$	Complex Gaussian random variable with mean a and variance b
$\mathcal{CN}(\mathbf{a}, \mathbf{B})$	Complex Gaussian random vector with mean vector \mathbf{a} and covariance matrix \mathbf{B}
$\text{Unif}[a, b)$	Uniform distribution in the interval $[a, b)$