

PERFORMANCE OF MASSIVE MIMO SYSTEMS WITH PRACTICAL HARDWARE CONSTRAINTS

SUDARSHAN MUKHERJEE



DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI

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PERFORMANCE OF MASSIVE MIMO SYSTEMS WITH PRACTICAL HARDWARE CONSTRAINTS

by

SUDARSHAN MUKHERJEE

DEPARTMENT OF ELECTRICAL ENGINEERING

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DEDICATED TO

My Parents

Certificate

This is to certify that the thesis entitled **Performance of Massive MIMO Systems with Practical Hardware Constraints** being submitted by **Mr. Sudarshan Mukherjee** to the Department of Electrical Engineering, Indian Institute of Technology Delhi (I.I.T. 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 my supervision. In my 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.

Date:

Place: Delhi

Dr. Saif Khan Mohammed

Associate Professor

Department of Electrical Engineering

Indian Institute of Technology Delhi

Delhi - 110016 (India)

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Abstract

The next generation (5G) wireless communication systems have been envisaged as an amalgamation of various disruptive technologies (e.g. device centric small cells, millimeter wave (mmWave), massive MIMO etc.) so that the key requirements of energy and spectral efficiency and low latency can be achieved. With the broadening of scope for technologies in 5G, recent research works have revealed that massive multiple-input multiple-output (MIMO) systems can be the perfect solution to support such an hybrid architecture of communication network.

In massive MIMO systems, while increasing the number of antennas (i.e. active RF chains) provides an inherent ability to suppress multi-user interference (MUI), it also imposes severe hardware constraints in terms of energy consumption, design complexity and implementation cost. It has however been observed that the massive MIMO systems can offer robust performance against various hardware impairments. Therefore non-ideal low-cost hardware and low-complexity signal processing techniques can be used for practical implementation of massive MIMO systems, while maintaining its promising improvement in energy efficiency (EE) and spectral efficiency (SE).

In our work, we focus on practical (non-ideal) hardware constraints from two specific aspects- (a) low-cost/low-complexity signal processing; and (b) practical implementation aspects of coherent detection. The low-cost/low-complexity signal processing aspect mainly focuses on reducing the energy consumption, design complexity and implementation cost. Therefore we first study the EE-SE trade-off in massive MIMO system, with optimal number of antennas so as to maximize the energy efficiency in the presence of transceiver power consumption. Our study reveals that it is EE optimal to have a large number of active base-station (BS) antennas (i.e. to operate in the massive MIMO regime), when the cell size is large or when the required spectral efficiency is high. On the other hand, with small

cells or with small SE requirement, it is EE optimal to operate with a single BS antenna (i.e. the non-massive MIMO regime).

From the study of energy efficiency (EE) versus spectral efficiency and cell size, it is revealed that in the massive MIMO regime of operation, almost 50% of the total transceiver energy consumption occurs at the PAs. Therefore from the EE perspective, high efficiency non-linear power amplifiers (PAs) are recommended for massive MIMO systems. To combat the effect of distortions due to non-linearity of high efficiency PAs, per-antenna constant envelope (CE) transmission has been recommended for the downlink operation in massive MIMO systems. In this direction, we address the issue of out-of-band emission at the output of non-linear PAs, by constraining the time-variation in the transmitted phase angles of the CE signal. Another important issue from the low-cost/low-complexity signal processing perspective is band pass filtering in massive MIMO uplink receiver (BS). In our work, we study the variation in the minimum required out-of-band attenuation for RF front end band pass filters with increasing number of BS antennas. Our analysis reveals that with increasing number of receiving (BS) antennas, the out-of-band attenuation requirement becomes more stringent. This shows that there is a practical limit on the number of active antennas that can be deployed in massive MIMO systems.

Next from the perspective of practical implementation of coherent multi-user detection, we investigate low-complexity frequency synchronization techniques in massive MIMO systems. Since the existing frequency synchronization techniques for conventional MIMO systems have prohibitive complexity with increasing number of users in the massive MIMO regime, we first propose a simple low-complexity correlation-based technique for estimating carrier frequency offsets (CFOs) in massive MIMO systems. This CFO estimation technique requires special impulse-like pilots. It is shown that the per-channel use complexity of the proposed CFO estimation algorithm is almost independent of the number of users, when the pilot length for CFO estimation is sufficiently large. Also, the performance of

the CFO estimator is observed to improve with both increasing number of BS antennas and also with increasing number of user terminals.

We also study the impact of residual CFO errors (after CFO estimation/compensation) on the information rate performance of massive MIMO systems. It is observed that with the proposed low-complexity CFO estimation/compensation technique, the minimum required per-user transmit power (to achieve a fixed desired information rate) decreases by roughly 1.5 dB, with every doubling in the number of BS antennas. This is interesting since the same decrease in the required per-user transmit power is also observed in the ideal/zero CFO scenario. In other words, with the proposed CFO estimation/compensation, the achievable array gain remains unchanged in the residual CFO scenario, compared to the ideal/zero CFO scenario.

Finally we address the issue of high peak-to-average power ratio (PAPR) impulse-like pilots used in the above mentioned correlation-based CFO estimation algorithm, since high PAPR pilots are susceptible to non-linear distortions in the channel. Therefore we propose a spatially averaged periodogram-based low-complexity CFO estimation technique that uses a set of special constant envelope (i.e. low-PAPR) pilots. The performance complexity trade-off between these two low-complexity CFO estimators shows that while the correlation-based CFO estimator discussed earlier is less complex, the new CE-pilot based CFO estimator is superior in terms of both energy and spectral efficiency, in low-mobility channels in massive MIMO systems.

सारांश

अगली पीढ़ी (५ जी) वायरलेस कम्युनिकेशन सिस्टम्स को विभिन्न विघटनकारी तकनीकों (जैसे दिवाइस सेन्ट्रिक स्मॉल सेल्स, मिलीमीटर वेव (एमएमवेव), मैसिव मीमो आदि) के एकीकरण के रूप में परिकल्पित किया गया है, ताकि एनर्जी और स्पेक्ट्रल एफिशिएंसी और कम लेटेंसी जैसी प्रमुख आवश्यकताएं प्राप्त की जा सकें। ५ जी में प्रौद्योगिकियों के दायरे के विस्तार के साथ, हाल के अनुसन्धान कार्यों से पता लगा है कि कम्युनिकेशन नेटवर्क की इस तरह के हाइब्रिड आर्किटेक्चर को समर्थन करने के लिए मैसिव मल्टी-इनपुट मल्टी-आउटपुट (मीमो) सिस्टम्स एकदम सही समाधान हो सकता है।

मैसिव मीमो सिस्टम्स में एन्टेना (अर्थात् सक्रिय आरेफ चैन) की संख्या में वृद्धि जैसे मल्टी-युजर इंटरफेरेंस को शमन करने की योग्यता प्रदान करता है, ऐसे ही वो एनर्जी की खपत, डिजाइन की जटिलता और लागत की मामले में कठोर हार्डवेयर कन्स्ट्रेंट को भी लागू करता है। हालांकि यह देखा गया है कि मैसिव मीमो सिस्टम्स विभिन्न हार्डवेयर खराबी के खिलाफ मजबूत प्रदर्शन कर सकता है। इसलिए एनर्जी एफिशिएंसी और स्पेक्ट्रल एफिशिएंसी की उन्नति करने के साथ साथ नौन-आइडियल कम मूल्य वाले हार्डवेयर और कम जटिलता वाले सिग्नल प्रोसेसिंग तकनीकों को मैसिव मीमो सिस्टम्स को व्यावहारिक कार्यान्वयन के लिए उपयोग किया जा सकता है।

हमारे काम में हम दो विशिष्ट पहलुओं से व्यावहारिक (नौन-आइडियल) हार्डवेयर प्रतिबन्ध पर ध्यान केन्द्रित करते हैं - (ए) कम मूल्य/कम जटिलता वाले सिग्नल प्रोसेसिंग; और (बी) कोहेरेंट डिटेक्शन का व्यावहारिक कार्यान्वयन पहलू। कम मूल्य/कम जटिलता वाले सिग्नल प्रोसेसिंग पहलू मुख्य रूप से एनर्जी खपत, डिजाइन की जटिलता और कार्यान्वयन की लागत को कम करने पर केन्द्रित है। इसलिए हम सबसे पहले ट्रान्सीवर एनर्जी खपत और एन्टेना की सर्वोत्कृष्ट संख्या के साथ मैसिव मीमो सिस्टम्स में ईई-एसई ट्रेड-ऑफ का अध्थयन करते हैं, जिससे कि एनर्जी एफिशिएंसी अधिकतम हो सके। हमारे अध्ययन से पता चला है कि जब सेल का आकार बड़ा हो या आवश्यक स्पेक्ट्रल एफिशिएंसी ज्यादा हो, तब सर्वोत्कृष्ट ईई प्राप्त करने के लिए बेस स्टेशन पर सक्रिय एन्टेना बहुत अधिक संख्या में होने चाहिए (अर्थात् मैसिव मीमो रेजीम में संचालन)। दूसरी ओर स्मॉल सेल या स्मॉल एसी पर सर्वोत्कृष्ट ईई प्राप्त करने के लिए एक ही बीएस एन्टेना से संचालन पर्याप्त है (अर्थात् नौन-मैसिव मीमो रेजीम)।

एनर्जी एफिशिएंसी बनाम स्पेक्ट्रल एफिशिएंसी और सेल की आकार की तुलना के अध्ययन से पता चला है कि मैसिव मीमो रेजीम में संचालन करने से कुल ट्रान्सीवर एनर्जी खपत के लगभग ५०% पीए पर ही होता है। इसलिए ईई परिप्रेक्ष्य से उच्च एफिशिएंसी नौन-लीनियर पावर एम्पलीफायर (पीए) को मैसिव मीमो सिस्टम्स के लिए अनुशंसित किया जाता है। उच्च एफिशिएंसी पीए को नौन-लीनियरिटी से उत्पन्न विकृति के प्रभाव का सामना करने के लिए मैसिव मीमो सिस्टम्स में डाउनलिक संचालन के लिए कांस्टेंट एनवलप (सीई) ट्रांसमिशन

को अनुशंसित किया गया है। इस दिशा में हम नौन-लीनियर पीए की आउटपुट में उत्पन्न आउट-औफ-बैंड एमिशन का समाधान करने के लिए सीई सिग्नल की ट्रांसमिटेड फेज एंगल की समय-भिन्नता को परिवर्द्ध करते हैं। कम मूल्य/कम जटिलता वाले सिग्नल प्रोसेसिंग परिप्रेक्ष्य से और एक महत्वपूर्ण मुद्दा है मैसिव मीमो आपलिक रिसीवर (बीएस) में बैंडपास फिल्टरिंग। हमारे काम में हम आरएफ फ्रंट एन्ड बैंडपास फिल्टर की न्यूनतम आवश्यक आउट-औफ-बैंड एटेनुअशन में एन्टेना की संख्या वृद्धि के साथ जो वदलाव आता है उसका अध्ययन करते हैं। हमारे विश्लेषण से पता चला है कि रिसीविंग (बीएस) एन्टेना की बढ़ती हुई संख्या के साथ आउट-औफ-बैंड एटेनुअशन की आवश्यकता भी अधिक अनम्य हो जाती है। इससे पता चलता है कि सक्रिय एन्टेना की संख्या पर एक व्यावहारिक सीमा है, जो मैसिव मीमो सिस्टम्स में तैनात की जा सकती है।

कोहेरेंट मल्टी-युजर डिटेक्शन की व्यावहारिक कार्यान्वयन की दृष्टिकोण से, आगे, हम मैसिव मीमो सिस्टम्स में कम जटिलता वाले फ्रीक्वेंसी सिंक्रोनाइजेशन तकनीकों की निरीक्षण करते हैं। क्योंकि परम्परागत मीमो सिस्टम्स का प्रचलित फ्रीक्वेंसी सिंक्रोनाइजेशन तकनीकों की जटिलता मैसिव मीमो रेजीम में बढ़ती हुई युजर संख्या के साथ साथ निषेधात्मक हो जाती है, इसलिए हम मैसिव मीमो सिस्टम्स में कैरियर फ्रीक्वेंसी ऑफसेट (सीएफओ) का आंकलन करने के लिए सबसे पहले एक सरल कम जटिलता वाले कोरिलेशन पर आधारित तकनीक का प्रस्ताव करते हैं। इस सीएफओ आंकलन तकनीक में इम्पल्स के तरह विशेष पायलट की आवश्यकता है। यह देखा गया है कि जब लंबाई पर्याप्त रूप से बड़ी होती है, तब प्रस्तावित सीएफओ आंकलन अल्गोरिदम की प्रति-चैनल उपयोग जटिलता लगभग युजर संख्या पर निर्भर नहीं करती है। इसके अलावा भी पर्यवेक्षण से पता चलता है कि बढ़ती हुई बीएस एन्टेना की संख्या और बढ़ती हुई युजर की संख्या के साथ इस सीएफओ आंकलन में और भी सुधार आता है।

आगे हम मैसिव मीमो सिस्टम्स की इनफार्मेशन रेट के ऊपर अवशिष्ट सीएफओ त्रुटियों (सीएफओ आंकलन और प्रतिकरण के पश्चात) के प्रभाव का भी अध्ययन करते हैं। यह देखा गया है कि इस प्रस्तावित कम जटिलता वाले सीएफओ आंकलन और प्रतिकरण तकनीक के साथ एक स्थिर वांछित इनफार्मेशन रेट के लिए जो न्यूनतम प्रति-युजर ट्रांसमिट पावर की आवश्यकता है, बीएस एन्टेना की संख्या में हर दोहरीकरण के साथ साथ उस पावर में लगभग १.५ डीबी घटाव होते हुए देखा जाता है। दूसरे शब्दों में यह कहा जा सकता है कि आदर्श/जीरो (zero) सीएफओ परिदृश्य की तुलना में प्रस्तावित सीएफओ आंकलन/प्रतिकरण के साथ प्राप्त एरे गेन (array gain) अपरिवर्तित रहता है।

अन्त में हम उपरोक्त कोरिलेशन-आधारित सीएफओ आंकलन अल्गोरिदम में प्रयुक्त इम्पल्स-जैसी उच्च पीक-टु-एवरेज-पावर अनुपात (peak-to-average-power ratio) (पीएपीआर) पायलट के मुद्दे पर ध्यान केन्द्रित करते हैं, क्योंकि चैनल में उपस्थित नौन-लीनियर विक्रतियों के लिए उच्च पीएपीआर पायलट अतिसंवेदनशील होते हैं। इसलिए हम एक स्पेशियली-एवरेजड पीरिओडोग्राम पर आधारित कम जटिलता वाले सीएफओ आंकलन तकनीक का प्रस्ताव रखते

हैं, जो एक विशेष कांस्टेंट एनवलप (कम पीएपीआर) पायलट समूह का उपयोग करता है। इन दोनों कम जटिलता वाले सीएफओ आंकलन तकनीकों के प्रदर्शन और जटिलता की ट्रेड-ऑफ से पता चलता है जहाँ पूर्वोक्त कोरिलेशन-आधारित सीएफओ आंकलन तकनीक की जटिलता अपेक्षाकृत कम होती है, उसकी तुलना में इस नयी सीई पायलट पर आधारित सीएफओ आंकलन तकनीक एनर्जी और स्पेक्ट्रल एफिशिएंसी के मामले में कम गतिशीलता वाले चैनल पर मैसिव मीमो सिस्टम्स के लिए बेहतर प्रदर्शन करती है।

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Abbreviations & Acronyms

ADC	Analog-to-Digital Converter
ATPC	Average only Total transmit Power Constraint
AWGN	Additive White Gaussian Noise
BPF	Bandpass Filter
BS	Base Station
CCI	Co-channel Interference
CE	Constant Envelope
CFO	Carrier Frequency Offset
CRLB	Cramer-Rao Lower Bound
CSI	Channel State Information
DAC	Digital-to-Analog Converter
DL	Downlink
DTCE	Discrete Time Constant Envelope
EINP	Effective In-band Noise Power
EE	Energy Efficiency
FDD	Frequency Division Duplexing
FIR	Finite Impulse Response
ICT	Information and Communication Technology
i.i.d.	independent and identically distributed
IMT	International Mobile Telecommunications
IoT	Internet of Things
IP	Internet Protocol

ISI	Inter-symbol Interference
ITRS	International Technology Roadmap for Semiconductors
ITU-R	International Telecommunication Union Radiocommunication Sector
KPI	Key performance Indicator
LMMSE	Linear Minimum Mean Squared Error
LOS	Line-of-sight
LSAS	Large Scale Antenna Systems
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
M2M	Machine-to-Machine
MAR	Maximum Allowable Ratio
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
ML	Maximum Likelihood
MMSE	Minimum Mean Squared Error
MRC	Maximum Ratio Combining
MRT	Maximum Ratio Transmission
MSE	Mean Squared Error
MUI	Multi-User Interference
NLS	Non-linear Least Squares
OFDM	Orthogonal Frequency Division Multiplexing
OOB	Out-of-band
OOBI	Out-of-band Interferer
OPEX	Operational Expenditure
PA	Power Amplifier
PAPC	Per-Antenna Power Constraint
PAPR	Peak-to-Average Power Ratio
PCP	Power Consumption parameters
PDP	Power Delay Profile
PPM	Parts Per Million
PSD	Power Spectral Density
QoS	Quality of Service
RAN	Radio Access Network
RF	Radio Frequency

RIBP	Received In-band Power
SCN	Small Cell Networks
SE	Spectral Efficiency
SINR	Signal-to-Interference and Noise Ratio
SIR	Signal-to-Interference Ratio
SISO	Single-Input Single-Output
SNR	Signal-to-Noise Ratio
TAPC	Total Transmit Power Constraint
TDD	Time Division Duplexed
TDM	Time Division Multiplexing
TR-MRC	Time-Reversal Maximum Ratio Combining
UL	Uplink
UT	User Terminal
VNI	Visual Network Index
ZF	Zero-Forcing

Notations

M	Number of Base-station Antennas
K	Number of Single Antenna User Terminals
N_u	Duration of uplink slot
N_c	Duration of Coherence Interval
B_w	Communication Bandwidth
γ	Signal-to-Noise Ratio (SNR)
Boldface lower case letters	Vectors
Boldface upper case letters	Matrices
j	$\sqrt{-1}$
$\Re(\cdot)$	Real part of the complex argument
$\Im(\cdot)$	Imaginary part of the complex argument
$(\cdot)^T$	Transposition operation
$(\cdot)^*$	Complex conjugation operation
$(\cdot)^H$	Hermitian Transposition operation
$\mathbb{E}[\cdot]$	Expectation Operator
$ \cdot $	Absolute value of a complex number
$\lceil c \rceil$	Smallest integer greater than c
$\ \cdot\ $	Euclidean norm of a vector
$tr(\cdot)$	Trace of a matrix
$det(\cdot)$	Determinant of a matrix
\mathbf{I}_N	Identity Matrix of Size $N \times N$
$\mathbf{1}$	Vector whose all components are 1

$\mathbf{1}_N$	Matrix of size $N \times N$ whose all components are 1
$\mathbf{0}$	An all 0 component vector
$[x]^+$	$\max(x, 0)$
$\mathcal{CN}(\mu, \sigma^2)$	Circular symmetric complex Gaussian distribution with mean μ and variance σ^2
\mathbb{R}	Field/Set of Real Numbers
\mathbb{C}	Field of Complex Numbers
\mathbb{Z}	Set of all Integers
\mathbb{Z}_+	Set of Positive Integers
$[a_{mk}]_{M \times K}$	An $M \times K$ matrix whose $(m, k)^{\text{th}}$ element is a_{mk}