

QUANTIZED FEEDBACK BASED PRECODING FOR MIMO SYSTEMS

ANKIT GARG



DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
DECEMBER 2018

©Indian Institute of Technology Delhi (IITD), New Delhi, 2018

QUANTIZED FEEDBACK BASED PRECODING FOR MIMO SYSTEMS

by

ANKIT GARG

DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

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

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI
DECEMBER 2018

Certificate

This is to certify that the thesis entitled "**Quantized Feedback Based Precoding for MIMO systems**" being submitted by **Mr. Ankit Garg** 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 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:
New Delhi

(Prof. Manav Bhatnagar)
Professor
Department of Electrical Engineering
Indian Institute of Technology Delhi

Acknowledgements

I would first like to thank my supervisor **Prof. Manav Bhatnagar** for his expert guidance, constant support, and immense encouragement throughout my Ph.D. program. His invaluable suggestions and insightful discussions made me enjoy my research. Also, his enormous enthusiasm, honest dedication, and the quest for knowledge are truly inspirational. My sincere appreciation also extends to Prof. R. K. Mallik, Prof. Shankar Prakriya, and Dr. Mahesh Abhegaonkar for their beneficial feedback and suggestions during my work.

I acknowledge my friends, Hari Krishna Boddapati, Sandeep Joshi, and Saptarishi Ghosh for helping me in various phases of my research work through numerous discussions and valuable inputs. I also thank my colleagues for sharing my joys and sorrows and the amazing time I spent with them. Without their help, I would have faced many difficulties in continuing my Ph.D. program.

Most importantly, I am indebted to my mother Mrs. Neerja for supporting me to do Ph.D., consistently being there with me at every phase and understanding me in every situation. Whatever I have achieved so far, I owe it to her sacrifices. I feel obligated for having supportive supervisor and friends. I feel blessed for their unconditional care and concern.

Ankit Garg

Abstract

In a practical wireless communication system, a transmitter needs to adapt its transmission depending upon the channel conditions, interference constraints, security constraints, etc. For this, the transmitter requires full channel state information (CSI) which is difficult to achieve in practice due to bandwidth constraints and channel coherence time limitations. On the other hand, exploiting channel statistics or providing partial CSI at the transmitter (CSIT) is practically more feasible. Therefore, quantized feedback based precoding schemes are quite useful for next generation wireless communication. In these schemes, instead of full CSI, index of the most favorable precoder matrix is conveyed from receiver to transmitter over a low-rate feedback link. However, due to the inevitable fading nature of the wireless feedback link, it is often unrealistic to obtain error-free feedback bits at the transmitter. The spurious feedback information drastically degrades the system performance. Thus, in this dissertation, we perform a detailed performance analysis of imperfect quantized feedback based precoding schemes over radio frequency (RF) and free space optical (FSO) communication systems. In particular, we explore how these schemes can be used to reduce the performance gap between orthogonal space-time block codes (OSTBCs) and beamforming with the help of partial CSIT. Further, a thorough comparison between existing precoding schemes with the proposed schemes is also performed. Moreover, we show that the considered precoding schemes are helpful in improving the secrecy gain of wiretap systems.

At first, we analyze the performance of feedback assisted diagonal precoding scheme over limited transmit antennas based RF-multiple-input single-output (MISO) communication system employing non-orthogonal STBCs and OSTBCs. The performance of the proposed error tolerant scheme is evaluated in terms of pairwise error probabil-

ity, bit error rate, and symbol error rate. Optimized transmit diagonal weights are obtained by minimizing the derived closed-form expression of error probability/rate. It is illustrated by numerical results that the proposed schemes remain insensitive to feedback error in comparison to the best transmit antenna selection (BTAS) scheme. Next, we propose a generalized diagonal precoding scheme for an arbitrary MISO system employing imperfect feedback. A new signal-to-noise ratio (SNR) adaptive scheme is also introduced which works very close to the BTAS scheme. Later, the error performance and ergodic rate of the SNR adaptive scheme are analyzed over large-scale multiple-input-multiple-output (MIMO) system. Further, we show that the proposed scheme outperforms the other considered weighted and unweighted schemes in term of all the investigated performance metrics.

An effective alternative to the existing RF communication and optical fibre communication is FSO communication; as it provides the speed of fiber optic cable and wireless connectivity. However, the performance of the FSO system is highly dependent on the atmospheric conditions and misalignment errors. Therefore, quantized feedback based beamforming schemes for an FSO MISO system under pointing error are proposed for erroneous feedback information. It is deduced that similar to RF communication, the proposed feedback based transmission schemes successfully achieve the maximal diversity order despite imperfect feedback. Further, it also observed that the proposed schemes provide noticeable coding gain under various atmospheric conditions including misalignment error. Moreover, it is shown that the feedback based precoding can be applied for attaining physical layer security. The secrecy performance gain is analytically characterized for the proposed diagonal precoding scheme.

सार

एक व्यावहारिक वायरलेस संचार प्रणाली में, ट्रांसमीटर को इसके संचरण को अनुकूलित करने की आवश्यकता होती है चैनल की स्थितियों, हस्तक्षेप की बाधाओं, सुरक्षा बाधाओं, आदि के आधार पर। इसके लिए, पूर्ण चैनल स्टेट इन्फर्मेशन (सीएसआई) की जानकारी की आवश्यकता है जिस्को वास्विकता में हासिल करना मुश्किल है बैंडविड्थ और चैनल अल्कन समय की बाधों के कारण। दूसरी ओर, चैनल के आंकड़ों का पता करना या आंशिक सीएसआई प्रदान करना ट्रांसमीटर पर व्यावहारिक रूप से अधिक व्यवहार्य है। इसलिए, मात्रा निर्धारित फीडबैक आधारित प्री-कोडिंग योजनाएं अगली पीढ़ी के वायरलेस संचार के लिए काफी उपयोगी हैं। इन योजनाओं में, पूर्ण सीएसआई की बजाय, सबसे अनुकूल प्री-कोडर मैट्रिक्स की अनुक्रमणिका को व्यक्त किया जाता है कम दर वाले फीडबैक लिंक पर रिसीवर से ट्रांसमीटर तक। हालांकि, वायरलेस फीडबैक लिंक की अपरिहार्य लुप्तप्राय प्रकृति के कारण, ट्रांसमीटर पर त्रुटि मुक्त फीडबैक बिट्स अक्सर प्राप्त करना अवास्तविक है। फीडबैक की गलत जानकारी सिस्टम के प्रदर्शन को काफी हद तक खराब कर देती है। इस प्रकार, इस शोध प्रबंध में, हम अपूर्ण मात्राबद्ध फीडबैक आधारित सटीक योजनाओं का विस्तृत प्रदर्शन विश्लेषण करते हैं रेडियो फ्रीक्वेंसी (आरएफ) और फ्री स्पेस ऑप्टिकल (एफएसओ) संचार प्रणालियों पर। विशेष रूप से, हम यह पता लगा रहे हैं कि ऑर्थोगोनल स्पेस-टाइम ब्लॉक कोड (ओएसटीबीसी) और बीमफॉर्मिंग के बीच प्रदर्शन अंतर को कम करने के लिए इस योजना का उपयोग कैसे किया जा सकता है मात्राबद्ध फीडबैक बिट्स के रूप में ट्रांसमीटर पर आंशिक चैनल की जानकारी की मदद से। इसके अलावा, प्रस्तावित के साथ मौजूदा प्री-कोडिंग योजनाओं के बीच पूरी तरह से तुलना भी की गई है। इसके अलावा, हम दिखाते हैं कि प्री-कोडिंग योजनाएं वायरलेस सिस्टम के प्रदर्शन में भी सुधार करने में सहायक हैं।

सबसे पहले, हम सीमित ट्रांसमिशन एंटेना (यानी 4 तक) और गैर-ऑर्थोगोनल एसटीबीसी और ओएसटीबीसी को नियोजित करने वाले एक रिसीवर के साथ आरएफ-एमआईएसओ संचार प्रणाली पर फीडबैक सहायक विकर्ण प्रीडोडिंग योजना के प्रदर्शन का विश्लेषण करते हैं। प्रस्तावित त्रुटि सहनशील योजना का प्रदर्शन जोड़ीदार त्रुटि संभावना के संदर्भ में मूल्यांकन किया जाता है, बिट त्रुटि दर, और प्रतीक त्रुटि दर; अनुकूलित ट्रांसमिशन विकर्ण वजन प्राप्त कर रहे हैं त्रुटि संभावना/ दर की व्युत्पन्न बंद-स्वरूप अभिव्यक्ति को कम करके। प्रस्तावित योजना त्रुटि फीडबैक के लिए असंवेदनशील बनी हुई है बेस्ट ट्रान्स्मिट एंटेना सिलेक्शन (बीटीएस) योजना की तुलना में यह

सचित्र है संख्यात्मक परिणामों से। आगामी, हम एमआईएसओ सिस्टम के लिए एक सामान्यीकृत विकर्ण प्री-कोडिंग योजना का प्रस्ताव देते हैं अपूर्ण फीडबैक की उपस्थिति में। एक नया सिग्नल-टू-नॉज़ रेशीओ (एसएनआर) अनुकूली योजना को भी पेश किया गया है जिसका प्रदर्शन लगभग बीटीएस योजना जैसा काम करता है। बाद में, एसएनआर अनुकूली योजना के त्रुटि प्रदर्शन और एर्गोडिक दर का विश्लेषण लार्ज स्केल एकाधिक मल्टिपल इनपुट- मल्टिपल -आउटपुट (एमआईएमओ) सिस्टम पर किया गया है। इसके अलावा, हम दिखाते हैं कि प्रस्तावित योजना अन्य भारित और अभारित योजनाओं में सबसे अच्छा प्रदर्शन करती है सभी जांच प्रदर्शन मीट्रिक की अवधि। मौजूदा आरएफ संचार और ऑप्टिक फाइबर संचार के लिए एक प्रभावी विकल्प एफएसओ संचार है क्योंकि यह फाइबर ऑप्टिक केबल की गति और वायरलेस की कनेक्टिविटी प्रदान करता है। हालांकि, एफएसओ प्रणाली का प्रदर्शन अत्यधिक निर्भर है वायुमंडलीय परिस्थितियों और मिसलायन्मेंट त्रुटियों पर। इसलिए, मात्राबद्ध फीडबैक आधारित सामान्यीकृत बीमफॉर्मिंग योजनाएं प्रस्तावित की गयी हैं पॉइंटिंग त्रुटि के तहत एफएसओ एमआईएसओ सिस्टम के लिए गलत फीडबैक जानकारी की उपास्थिति में। इसके अलावा, यह अनुमान लगाया जाता है आरएफ संचार के समान, प्रस्तावित फीडबैक आधारित सटीक योजनाएं सफलतापूर्वक अधिकतम डिवर्सिटी ऑर्डर और महत्वपूर्ण कोडिंग लाभ प्रदान करती हैं बावजूद मिसलायन्मेंट त्रुटि सहित विभिन्न वायुमंडलीय स्थितियों के तहत अपूर्ण फीडबैक की जानकारी समेत। इसके अलावा, प्रस्तावित फीडबैक आधारित प्रीडोडिंग योजनाओं का आवेदन किया जाता है भौतिक परत सुरक्षा के लिए। विश्लेषण से पता चलता है कि प्रस्तावित एरर टॉलरेंट योजनाएं एक महत्वपूर्ण प्रदर्शन लाभ प्रदान करती हैं।

Table of Contents

Certificate	i
Acknowledgements	ii
Abstract	iii
List of Figures	xii
List of Tables	xiii
Abbreviations	xiv
1 Introduction	1
1.1 Introduction	1
1.1.1 Precoding	1
1.1.2 Space-Time Block Coding	2
1.1.3 MIMO Communication	2
1.1.4 FSO Communication	3
1.1.5 CSIT Acquisition Techniques	4
1.2 Literature Review	4
1.3 Motivation	6
1.4 Thesis Statement and Contributions	7
1.5 Outline of Thesis	8
2 Feedback Based Diagonal Precoding for RF-MISO systems with Limited Transmit Antennas	10

2.1	Introduction	10
2.2	One Bit Feedback Based Diagonal Precoding for NOSTBCs	11
2.2.1	Review of Golden and Silver STBCs	11
2.2.2	System Model	12
2.2.3	Diagonal Precoding for 2×1 MISO System	13
2.2.4	Computation of PEP	13
2.2.5	Numerical Results	15
2.3	Diagonal Precoding for Alamouti STBC over Nakagami- m Fading Channels	17
2.3.1	System Model and Channel Model	17
2.3.2	Computation of the Average BER	18
2.3.3	Computation of Ergodic Capacity	20
2.3.4	Numerical Results	21
2.4	Diagonal Precoding for 4×1 MISO System with ROSTBCs	22
2.4.1	System Model	23
2.4.2	Precoder Design	24
2.4.3	Computation of the Average SER	26
2.4.4	Numerical Results	27
2.5	Conclusions	28
3	Limited Feedback Based MISO and LS-MIMO RF Communication Systems	30
3.1	Introduction	30
3.2	Imperfect Feedback Based $n_t \times 1$ RF-MISO System	32
3.2.1	System model	32
3.2.2	Precoder Design	33
3.3	Performance Analysis	36
3.3.1	Average SER	36
3.3.2	Average SER of Error-Tolerant Weighing Scheme	39

3.3.3	Ergodic Capacity	40
3.4	Numerical Results	42
3.5	Erroneous Feedback Based LS-MIMO System Over Nakagami- m Fading Channels	48
3.5.1	System Model	48
3.6	Error Rate Assessment	49
3.6.1	Computation of SER	50
3.6.2	Asymptotic Analysis	52
3.6.3	BTAS Scheme Under Erroneous Feedback	57
3.6.4	Average SER of Error-Tolerant Weighing Scheme	58
3.6.5	Precoder with More Than Two Optimization Parameters	59
3.7	Ergodic-Rate Analysis	61
3.8	Numerical Results	62
3.9	Conclusions	71
4	Imperfect Quantized Feedback Based Beamforming for FSO MISO System over G-G Fading with Pointing Errors	73
4.1	Introduction	73
4.2	System Model	74
4.2.1	Channel Model	76
4.2.2	Beamforming Scheme for $n_t \times 1$ FSO MISO system	77
4.3	Average BER Analysis	78
4.3.1	Transmit Aperture Selection Scheme with Erroneous Feedback	79
4.3.2	Error Tolerant Beamforming Scheme	80
4.4	Ergodic Capacity Analysis	85
4.4.1	Transmit Aperture Selection Scheme with Erroneous Feedback	85
4.4.2	Error Tolerant Beamforming Scheme	86
4.5	Numerical Results	87
4.6	Conclusions	95

5	Secrecy Performance of Imperfect One-Bit-Feedback Based Alamouti	
	MISO System	97
5.1	Introduction	97
5.2	System Model	99
5.3	SOP Analysis	100
5.3.1	Exact SOP Analysis	101
5.3.2	Asymptotic SOP Analysis	102
5.4	Numerical Results	104
5.5	Conclusions	106
6	Conclusions and Scope for Future Work	107
6.1	Conclusions	107
6.2	Future Work	109
	Bibliography	110
	Publications based on this Thesis	120
	Technical Biography of Author	122

List of Figures

2.1	Block diagram of a 2×1 MISO system with precoder, quantized feedback, and NOSTBC.	12
2.2	The PEP of Golden and Silver Codes employing 4-QAM constellation when symbol x_1 of \mathbf{X} is in error for various values of P_c for SNR = 20 dB.	15
2.3	Simulated PEP performance of Golden code with and without feedback for 4-QAM in a 2×1 MISO system.	16
2.4	Comparison of the simulated PEP performance of Golden and Silver codes with ($a^2 = 1$) and without ($a^2 = 0.5$) feedback employing 4-QAM constellation.	16
2.5	BER versus SNR plots of the Alamouti STBC with optimized power allocation (analysis with 1% $\text{---}\triangle\text{---}$ and 5% $\text{---}\circ\text{---}$ feedback errors and simulation \square) and uniform power allocation (analysis $\text{---}+\text{---}$). The analytical performance (with 1% $\text{---}\times\text{---}$ and 5% $\text{---}\ast\text{---}$ feedback errors) of the best antenna selection based diagonal precoding scheme is also shown.	21
2.6	Analytical $\text{---}\ast\text{---}$ and simulated \diamond capacity versus SNR plots of the Alamouti STBC with optimized and uniform power allocation; $P_c = 0.99$ and $m = 3$	22
2.7	Block diagram of a 4×1 MISO system with precoder, quantized feedback, and ROSTBC.	23
2.8	The SER of ROSTBC employing 4-PAM constellation for various values of P_c for SNR = 20 dB; a_0^2 denotes the optimized value of a^2	27
2.9	Analytical $\text{---}+\text{---}$ and Simulated \square SER performance of ROSTBC with and without feedback, and Simulated --- Beamforming for 4-PAM 4×1 MISO system.	28

3.1	Block diagram of an $n_t \times 1$ MISO system with proposed quantized $\lceil \log_2 n_t \rceil$ bits feedback based precoder; $\lceil \cdot \rceil$ denotes the ceiling function.	32
3.2	Coding gain advantage (ΔG_c) of the BTAS scheme over UPA with respect to number of transmit antennas (n_t).	38
3.3	Optimization of the error-tolerant parameter a_1 by minimization of the SER given in (3.12) for 4×1 MISO system over various values of P_c for SNR = 20 dB, a_1^* denotes the optimized value of a_1	44
3.4	Simulated and analytical SER versus SNR plots of 4×1 MISO system with and without feedback error.	45
3.5	Comparison of SER performance between UPA and BTAS ($P_c = 1$) for 2×1 , 4×1 , 8×1 , and 16×1 MISO systems employing 4-QAM constellation.	46
3.6	Simulated and analytical capacity versus SNR of the Alamouti-STBC with and without feedback error.	46
3.7	Simulated and analytical capacity versus SNR performance Alamouti-STBC for 2×1 MISO system with and without and the proposed ETW schemes.	47
3.8	Comparison of capacity versus SNR performance between UPA and BTAS schemes ($P_c = 1$) for 2×1 , 4×1 , 8×1 , and 16×1 MISO systems.	47
3.9	Block diagram of an $n_t \times n_r$ LS-MIMO wireless communication system with proposed quantized $\lceil \log_2 n_t \rceil$ bits feedback-based precoder.	48
3.10	Coding gain advantage ($\Delta G_c^{BTAS-UPA}$) of the BTAS scheme over UPA with respect to n_t and n_r for $m = 1.25$ obtained with the help of (3.47).	55
3.11	Optimization of the error-tolerant parameter a_1 by minimization of the SER given in (3.39) for 2×2 MIMO system over various values of P_c for SNR = 20 dB, $m = 2$, a_1^* denotes the optimized value of a_1	63
3.12	Simulated and analytical SER performance of Alamouti-STBC for $m = 2$ over 2×2 MIMO system with and without feedback employing 16-QAM constellation and ETW schemes and Simulated Beamforming.	64
3.13	Optimization of the error-tolerant parameter a_1 by minimization of the SER given in (3.39) for 8×4 MIMO system over various values of P_c for SNR = 20 dB, $m = 1.25$, a_1^* denotes the optimized value of a_1	65

3.14	Analytical exact and asymptotic SER performance of OSTBC of 8×4 MIMO system for $m = 1.25$ and 2.5 with and without feedback employing 4-QAM constellation and ETW schemes.	66
3.15	Comparison of SER performance between diagonal precoder, unitary precoder and antenna subset selection for $m = 1$ over 4×2 MIMO system employing 16-QAM constellation under erroneous feedback.	67
3.16	Comparison of analytical SER performance between UPA ‘-.’ and BTAS scheme ‘--’ ($P_c = 1$) among 16×8 ‘o’, 32×4 ‘+’, 64×2 ‘◇’, and 128×2 ‘★’ for $m = 2$	68
3.17	Optimization of the error-tolerant parameters a_1 and a_2 by minimization of the SER of three parameters based precoder given in (3.62) for 3×1 MISO system over $P_c = 0.8$ for SNR = 20 dB.	68
3.18	Comparison of SER performance between the BTAS scheme ‘★’, UPA ‘□’, and ETW scheme based on diagonal precoders with two parameters ‘◇’ and with three parameters ‘o’ for 3×1 MISO system over different values of m (analytical $m = 1$ from (3.62) and simulated for $m = 2, 3$) with $P_c = 0.8$	69
3.19	Analytical ergodic-rate versus SNR performance OSTBC for $m = 1$ over 8×4 MIMO system with and without feedback error and the proposed ETW schemes.	70
3.20	Comparison of ergodic-rate versus SNR performance between UPA ‘-.’ and BTAS ‘--’ schemes ($P_c = 1$) for 16×8 ‘o’, 32×4 ‘+’, and 64×2 ‘□’ with $m = 3$	70
4.1	Block diagram of the proposed $n_t \times 1$ FSO MISO system with beamforming vector.	75
4.2	Optimization of error tolerant parameter a by minimization of (4.35) over ST for $n_t = 3$ and 4 with $P_c = 0.5, 0.7, 0.95, 0.95, 0.99$, pointing error parameter $\xi^2 = 1.7$, and path loss component $h_{pl} = 1$	88
4.3	Optimization of error tolerant parameter a by minimization of (4.35) over MT for $n_t = 3$ and 4 with $P_c = 0.5, 0.7, 0.95, 0.95, 0.99$, pointing error parameter $\xi^2 = 1.7$, and path loss component $h_{pl} = 1$	89

4.4	Simulated and analytical BER performance of 3×1 FSO MISO system with and without feedback error and ETW schemes under ST perturbed G-G fading channels with pointing error parameter $\xi^2 = 1.7$ and path loss component $h_{pl} = 1$	91
4.5	Analytical BER performance of 4×1 FSO MISO system with and without feedback error and ETW schemes under MT perturbed G-G fading channels with pointing error parameter $\xi^2 = 1.7$ and path loss component $h_{pl} = 1$	91
4.6	Analytical asymptotic upperbound BER performance of 6×1 FSO MISO system with and without feedback error and ETW schemes under ST perturbed G-G fading channels with pointing error parameter $\xi^2 = 1.7$, path loss component $h_{pl} = 0.9$, and $A_0 \approx 0.3$ over visibility = 10 Km.	93
4.7	Comparison of analytical asymptotic upperbound BER performance of new SAETW beamforming scheme between $-- 8 \times 1$, $-\cdot- 12 \times 1$, and $- 16 \times 1$ each over ST ‘o’ and MT ‘★’ with pointing error $\xi^2 = 1.2$ and path loss component $h_{pl} = 1$	94
4.8	Capacity performance of 4×1 FSO MISO system with and without feedback error and ETW schemes under ST with G-G fading channels and pointing error parameter $\xi^2 = 1.7$ and path loss component $h_{pl} = 1$	94
5.1	MISO wiretap channel with one bit feedback based precoder.	98
5.2	SOP of the considered MISO system with ETW scheme versus a_1 for different values of P_c and a_1 with $\bar{\gamma}_E = 5$ dB.	105
5.3	Comparison of SOPs of the BTAS and UPA schemes with ETW scheme that uses optimum value of a_1 with $\bar{\gamma}_E = 5$ dB.	106

List of Tables

2.1	Error-tolerant weighing parameter a^2 for NOSTBCs using QAM constellation with $P_c = 0.95$	14
3.1	Variation of schemes with probability of correct detection P_c and error-tolerant parameter a_1	43
4.1	Turbulence Parameters in MT and ST over FSO Link distance, $L = 1$ Km and wavelength, $\lambda = 1550$ nm.	87
4.2	System settings Under the Occurrence of pointing error	87
4.3	Optimized value of error tolerant parameter 'a' for different values of P_c over ST and MT with pointing error ($\xi^2 = 1.7$).	88
4.4	Design margin ($\Delta D_{SCH2}^{SCH1} = \text{SNR of SCH1} / \text{SNR of SCH2}$ where SCH stands for scheme) of Unweighted (Repetition coding), proposed FSETW scheme, and erroneous feedback (BTAS(erronoeus)) with respect to BTAS for 4×1 system over MT with pointing error $\xi^2 = 1.7$, $P_c = 0.95$, and $\delta = 1.7$ at BER $= 10^{-8}$	90

Abbreviations

AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BTAS	Best Transmit Antenna/Aperture Selection
CDF	Cumulative Distribution Function
CSI	Channel State Information
CSIT	Channel State Information at the Transmitter
ETW	Error Tolerant Weighing
FSO	Free Space Optical
G-G	Gamma-Gamma
GOSTBCs	Generalized Orthogonal Space Time Block Codes
i.i.d.	independent identically distributed
L -ASK	L -ary Amplitude Shift Keying
LOS	Line Of Sight
LS-MIMO	Large Scale-Multiple-Input Multiple-Output
MGF	Moment Generating Function
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
M -PAM	M -ary Pulse Amplitude Modulation
M -PSK	M -ary Phase Shift Keying
M -QAM	M -ary Quadrature Amplitude Modulation
MRT	Maximal Ratio Transmission
MT	Moderate Turbulence

NOSTBCs	Non Orthogonal Space-Time Block Codes
OSTBCs	Orthogonal Space-Time Block Codes
PEP	Pairwise Error Probability
PDF	Probability Density Function
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
ROSTBCs	Real Orthogonal Space Time Block Codes
RVQ	Random Vector Quantization
SER	Symbol Error Rate
SIM	Subcarrier Intensity Modulation
SNR	Signal-to-Noise Ratio
SOC	Secrecy Outage Coding
SOD	Secrecy Outage Diversity
SOP	Secrecy Outage Probability
ST	Strong Turbulence
STBCs	Space Time Block Codes
TAS	Transmit Antenna/Aperture Selection
UPA	Uniform Power Allocation
VQ	Vector Quantization