Declaration

I hereby declare that the work presented in this thesis titled *Massive MIMO Systems: Channel Modeling and Efficient System Architecture* submitted to the Indian Institute of Technology Jodhpur in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy, is a bonafide record of the research work carried out under the supervision of Dr. Arun Kumar Singh. The contents of this thesis in full or in parts, have not been submitted to, and will not be submitted by me to any other Institute or University in India or abroad for the award of any degree or diploma.

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Certificate

This is to certify that the thesis titled *Massive MIMO Systems: Channel Modeling and Efficient System Architecture*, submitted by *Suresh Dahiya (PG201282009)* to the Indian Institute of Technology Jodhpur for the award of the degree of *Doctor of Philosophy*, is a bonafide record of the research work done by him under my supervision. To the best of my knowledge, the contents of this report, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Arun Kumar Singh
Ph.D. Thesis Supervisor

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List of Symbols

Symbol	Description
N	Number of base station antennas
N_{stp}	Number of steps
N_c	Number of clusters
K	Number of mobile terminals in a cell
T	Number of symbols in a resource block
B	Bandwidth of signal
L	Number of cells in the system
M	Modulation order
C	Number of iterations of an algorithm
β	Average channel gain from mobile terminal to base station
t^b	Index of a resource block over time
f^b	Index of a resource block over frequency
T^b	Total number of resource blocks over time
F^b	Total number of resource blocks over frequency
$\mathbf{G}$	Overall channel matrix
$\mathbf{g}_i$	i^{th} column vector of $\mathbf{G}$
g_{ij}	$(ij)^{th}$ entry of $\mathbf{G}$
$\mathbf{H}$	Small scale fading channel matrix
$\mathbf{h}_i$	i^{th} column vector of $\mathbf{H}$
h_{ij}	$(ij)^{th}$ entry of $\mathbf{H}$
$\tilde{\mathbf{H}}_{PBE}$	Pilot based estimate of small scale fading channel matrix
$\mathbf{D}$	large scale fading plus path loss channel matrix
$\circ$	Hadamard product
$\mathbb{CN}$	Circulary symmetric complex normal distribution
Σ	Covariance matrix
$\sum_{j=1}^{K}$	Summation from $j = 1$ to $j = K$
α_b	Correlation between channel matrices of consecutive resource blocks
α_e	Correlation between estimated channel matrix of current resource blocks and actual channel matrix of previous resource block
$\mathbb{V}ar$	Statistical variance
$\mathbb{C}orr$	Correlation
$\triangleq$	Defined as
$\mathbb{E}$	Mathematical expectation
γ	Transmit power scaling factor
ε	A fraction of unity
τ	Pilot length
$\mathbf{S}$	Power scaling factor matrix
tr	Trace of a matrix
p_u	Measure of common transmit power
ρ	Measure of inter-cell interference power
$\mathbf{W}$	Additive white Gaussian noise matrix
$\mathbf{I}$	Identity matrix

Symbol	*Description*
$\mathbf{y}$	Signal vector $(N \times 1)$ at N antennas of base station
$\mathbf{Y}$	Signal matrix $(N \times T)$ at N antennas of base station for T channel usage
$< . >^{T}$	Transpose of $< . >$
$< . >^{H}$	Hermitian transpose of $< . >$
$< . >^{\dagger}$	Pseudo inverse of $< . >$
$< . >^{*}$	Complex conjugate of $< . >$
$\| < . > \|$	Frobenius norm of $< . >$
g_{ij}, h_{ij}	(ij)th entry of matrix $\mathbf{G}$, $\mathbf{H}$

List of Abbreviations

Abbreviation	*Full form*
2-D	Two Dimensional
3-D	Three Dimensional
AoA	Angle of Arrival
AoD	Angle of Departure
AWGN	Additive White Gaussian Noise
BLUE	Best Linear Unbiased Estimator
bpcu	Bit Per Channel Use
BS	Base Station
CBSCM	Correlation Based Stochastic Channel Models
CDF	Cummulative Distribution Function
CoMP	Coordinated Multi-Point
CSIR	Channel State Information at Receiver
DFT	Discrete Fourier Transform
DL	Downlink
EE	Energy Efficiency
EVD	Eigenvalue Decomposition
FDD	Frequency Division Duplex
GBSCM	Geometry Based Stochastic Channel Models
GLRT	Generalized Likelihood Ratio Test
i.i.d.	Independent and Identically Distributed
IBE	Iteration Based Estimation
ILSP	Iterative Least Square Projection
ITU-R	International Telecommunications Union-Radio
KBSCM	Kronecker-based Stochastic Channel Model
LAR	Least Absolute Residual
LLR	Log Likelihood Ratio
LOS	Line-of-sight
LTE	Long Term Evolution
METIS	Mobile and Wireless Communications Enablers for Twenty-twenty Information Society
MF	Match Filtering

Abbreviation	*Full form*
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MPC	Multi Path Component
MT	Mobile Terminal
NLOS	Non Line-of-sight
OFDM	Orthogonal Frequency Division Multiplexing
PBE	Pilot Based Estimation
PEACH	Polynomial ExpAnsion CHannel
PLL	Phase Lock Loop
QAM	Quadrature Amplitude Modulation
RB	Resource Block
SEP	Symbol Error Probability
SIF	Standard Interfrence Function
SNR	Signal to Noise Ratio
SVD	Singular Value Decomposition
TDD	Time Division Duplex
UL	Uplink
ULA	Uniform Linear Array
V-BLAST	Vertical Bell Laboratory Layered Space-Time
VCR	Virtual Channel Representation
VR	Visibility Region
WLAN	Wireless Local Area Network
WSMSE	Weighted Sum Mean Square Error
ZF	Zero Forcing