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APPENDICES

Appendix A

Definition (Meijer *G*-function)

The Meijer *G*-function is a generalization of the generalized hypergeometric function and may be defined using the contour ℓ integral representation

$$G_{p,q}^{m,n}\left[z \left| \begin{matrix} a_1,\ldots,a_n, a_{n+1}\ldots,a_p \\ b_1,\ldots,b_m, b_{m+1}\ldots,b_q \end{matrix} \right. \right]$$

$$= \frac{1}{j2\pi} \int_{\ell} \frac{\prod_{i=1}^{m}\Gamma(b_i+s)\prod_{i=1}^{n}\Gamma(1-a_i-s)}{\prod_{i=n+1}^{p}\Gamma(a_i+s)\prod_{i=m+1}^{q}\Gamma(1-b_i-s)} z^{-s} ds,$$

where z, $\{a_i\}_{i=1}^{p}$, and $\{b_i\}_{i=1}^{q}$ are, in general, complex-values. There are three possible definitions for the integration contour ℓ. With the parameter values occurring in this paper the contour ℓ is a left loop, which starts and ends at $-\infty$ and encircles all poles of $\Gamma(b_i+s)$ in the positive direction; in this case the function is analytic for $0<|z|<1$.

Appendix B

Derivation of Noise Covariance Matrix

We derive the covariance matrix of the effective zero-forcing processing noise in the presence of estimation error and feedback delay

$$E\left[\hat{\mathrm{n}}\hat{\mathrm{n}}^H\right]=E\left[\frac{1}{\rho}\mathbf{H}^{\dagger}\mathrm{n}-\frac{1}{\rho^2}\left(\mathbf{H}^{\dagger}\mathbf{E}\mathbf{F}\mathrm{s}+\mathbf{H}^{\dagger}\mathbf{E}\mathrm{n}\right)-\frac{\sqrt{1-\rho^2}}{\rho^2}\left(\mathbf{H}^{\dagger}\mathbf{H}_{\Delta t}\mathbf{F}\mathrm{s}+\mathbf{H}^{\dagger}\mathbf{H}_{\Delta t}\mathbf{H}^{\dagger}\mathrm{n}\right)\right.$$

$$\left.\times\left(\frac{1}{\rho}\mathbf{H}^{\dagger}\mathrm{n}-\frac{1}{\rho^2}\left(\mathbf{H}^{\dagger}\mathbf{E}\mathbf{F}\mathrm{s}+\mathbf{H}^{\dagger}\mathbf{E}\mathrm{n}\right)-\frac{\sqrt{1-\rho^2}}{\rho^2}\left(\mathbf{H}^{\dagger}\mathbf{H}_{\Delta t}\mathbf{F}\mathrm{s}+\mathbf{H}^{\dagger}\mathbf{H}_{\Delta t}\mathbf{H}^{\dagger}\mathrm{n}\right)\right)^H\right]$$

Here, we use the fact that

$$\begin{cases}\mathbf{H}^{\dagger}\left(\mathbf{H}^{\dagger}\right)^H=\left(\mathbf{H}^H\mathbf{H}\right)^{-1},\\[2ex] E\left[\mathrm{s}\mathrm{s}^H\right]=\mathrm{P}_s\mathbf{I}_{\mathrm{N_T}},\\[2ex] E\left[\mathbf{E}\mathbf{E}^H\right]=\mathrm{N_T}\mathbf{I}_{\mathrm{N_R}},\text{and}\\[2ex] E\left[\mathbf{E}\left(\mathbf{H}^H\mathbf{H}\right)^{-1}\mathbf{E}^H\right]=\mathrm{Tr}\left(\left(\mathbf{H}^H\mathbf{H}\right)^{-1}\right)\mathbf{I}_{\mathrm{N_R}}.\end{cases}$$

Appendix C

Abbreviations and Notations

Abbreviations

2G	Two Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
3GPP2	Third Generation Partnership Project 2
4G	Fourth Generation
AMPS	Advanced Mobile Phone System
AoA	Angle of Arrival
AoD	Angle of Departure
ASICs	Application Specific Integrated Circuits
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BLAST	Bell labs Layered Space Time
bps/Hz	bits per second per Hertz
BS	Base Station
CCSG	Complex Circularly Symmetric Gaussian
CDF	Cumulative Distribution Function
CDMA2000	Code Division Multiple Access 2000
CPDH	Complex Positive Definite Hermitian
CRM	Complex Random Matrix
CSI	Channel State Information
dB	deciBel
DSP	Digital Signal Processing
FDD	Frequency Division Duplexing
FOMA	Freedom of Mobile databox Access
FPGA	Field Programmable Gate Arrays

GSM	Global System for Mobile communication
HSDPA	Speed Downlink Packet Access
IEEE	Institute of Electrical and Electronics Engineers
IEICE	Institute of Electronics, Information and Communication Engineers
iid	independent identically distributed
IMT-2000	International Mobile Telecommunications 2000
IPv6	Internet Protocol version 6
IS-95	Interim Standard 95 (the first CDMA system adopted by the American TIA)
ITU-R	International Telecommunication Union Radio-communication sector
Kbps	Kilobit per second
LMMSE	Linear Minimum Mean Square Error
LOS	Light of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
Mbps	Megabit per second
MGF	Moment Generating Function
MI	Mutual Information
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
ML	Maximum Likelihood
MMSE	Minimum Mean Square Errors
Mo-IP	Mobile over Internet Protocol
M-PSK	M-ary Phase Shift Keying
M-QAM	M-ary Quadrature Amplifier Modulation
MS	Mobile Station
NLoS	Non Light of Sight
NTT - DoCoMo	Nippon Telegraph and Telephone - Do Communications on the Mobile network
OFDM	Orthogonal Frequency Division Multiplexing
pdf	probability density function
QoS	Quality of Service

rv	random variable
Rx	Receiver
SER	Symbol Error Rate
SIC	Successive Interference Cancellation
SIMO	Multiple Input Multiple Output
SINR	Signal-to-Interference-and-Noise Ratio
SIR	Signal-to-Interference Ratio
SISO	Single Input Single Output
SM	Spatial Multiplexing
SNR	Signal-to-Noise Ratio
SVD	Singular Value Decomposition
TDD	Time Frequency Duplexing
Tx	Transmitter
UMTS	Universal Mobile Telecommunications Systems
W-CDMA	Wideband-Code Division Multiple Access
WLAN	Wireless Local Area Networks
ZF	Zero Forcing
ZMCSCG	Zero Mean Circularly Symmetric Complex Gaussian

Notations

Some specific sets

$\mathbb{N}$	Nature number
$\mathbb{C}$	Complex numbers
$\mathbb{R}$	Real numbers

Scalars

x	The scalar x
N_{T}	Number of transmit antennas
N_{R}	Number of receive antennas
n	Minimum number of transmit and receive antennas
j	The imaginary unit $(j = \sqrt{-1})$

W	Bandwidth
N_0	Power spectral density of white Gaussian noise
P	Average power constraint measured in watts
SNR	Signal-to-Noise Ratio
η	Normalized average SNR per receive antenna under the power normalization
M	Constellation size
N	Degree of freedom
ρ	Correlation coefficient
d_{BS}	Antenna spacing at BS
d_{MS}	Antenna spacing at MS
d	Distance between BS and MS
r	Radius of the ring of scatterers
Δ	The angle spread
θ	The angle-of-departure at MS
Ω	The angle-of-arrival at BS

Capacities

$E[C]$	The mean (average) capacity
C_{SISO}	Capacity of conventional single-input single output (SISO) system
C_{SIMO}	Capacity of SIMO system
C_{MISO}	Capacity of MISO system
C_{MIMO}	Capacity of MIMO system
P_{out}	Outage probability of a scalar fading channel
$\Pr(\cdot)$	Error probability
$I_{\mathrm{lb}}^{\mathrm{iid}}(\cdot)$	Lower bound mutual information of iid channel
$I_{\mathrm{lb}}^{\mathrm{corr}}(\cdot)$	Lower bound mutual information of correlated channel

Vectors and matrices

$\mathbf{x}$	Vector channel input

y	Vector channel output
h	Vector, complex valued, channel
n	Vector white noise
h^*	Complex conjugate of h
$\mathbf{H}$	Matrix, complex valued, channel
$\hat{\mathbf{H}}$	Matrix, complex valued, estimated channel of $\mathbf{H}$
$\mathbf{H}_w$	Matrix, white random entries
$\mathbf{H}^\dagger$	Complex conjugate-transpose of $\mathbf{H}$
X	The vector or matrix X
$\mathbf{I}_n$	The identity matrix dimension $n \times n$
$h(\cdot)$	The different entropy
$\mathrm{eig}(\cdot)$	The diagonal matrix of eigenvalues of the quadratic matrix
P_{out}	Outage probability
$\mathbf{\Psi}_T, \mathbf{\Psi}_R$	The covariance matrices at the transmit and the receive antennas, respectively

Operations

$E[\cdot]$	Statistic expectation
$\mathrm{tr}(\cdot)$	The trace of a matrix
$\otimes$	The Kronecker product
$\sim$	As distributed as
$\approx$	As approximated as
$\triangleq$	As defined as
$[\cdot]_{i,j}$	$(i,j)th$ element of a matrix
$\lvert\cdot\rvert$	The determinant of a matrix, or cardinality of a set, or magnitude of an element
$(\cdot)^T$	The transpose
$(\cdot)^H$	The conjugate transpose
$(\cdot)^\dagger$	Moore-Penrose inverse (pseudo-inverse)

$(\cdot)^*$	The complex conjugate
$CN(\cdot,\cdot)$	Complex normal distribution with mean and covariance as first and second parameter, respectively
$N(\cdot,\cdot)$	Normal distribution with mean and covariance as first and second parameter, respectively
$\min\{\cdot\}$	The minimization
$\max\{\cdot\}$	The maximization
$I(\cdot;\cdot)$	The mutual information
$I_0(\cdot)$	The zero order modified Bessel function
$J_0(\cdot)$	The Bessel function of the first kind of the zero order

Appendix D

Publications and Presentations

International Journal Papers

[1] H.D. Trung, W. Benjapolakul, and K. Araki, "Capacity Analysis of MIMO Rayleigh Channel with Spatial Fading Correlation," IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences - Special Issue in Information Theory and Its Applications 2008, Vol.E91-A, No.10, Oct. 2008, pp.2818-2826.

International Conference Papers

[2] H.D. Trung, W. Benjapolakul, and K. Araki, "Ergodic capacity of MIMO Rayleigh channel with spatial fading correlation," in Proceedings of the International Symposium on Multimedia and Communication Technology (ISMAC2009), Jan. 22-23, 2009, Bangkok, Thailand.

[3] H.D. Trung, W. Benjapolakul, and K. Araki "A Study on the Channel Capacity of Multiple-Input Multiple-Output (MIMO) Wireless Systems," in Proceedings of the IEEE International Conference on Wireless and Optical Communication Networks 2007 (WOCN '07), Grand Hyatt Singapore, July 2nd-4th, 2007, pp. 1-6.

[4] H.D. Trung and W. Benjapolakul, "On Ergodic and Outage Capacities of Space-Time MIMO Channels," in Proceedings of 3th International Conference Engineering and Environment (ICEE 2007), Phukhet, Thailand, May 10 -11, 2007.

VITAE

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