## Random Matrix Methods for Wireless Communications

Z- CEIL

Romain Couillet and Merouane Debbah

CAMBRIDGE

## Random Matrix Methods for Wireless Communications

Romain COUILLET and Mérouane DEBBAH May 23, 2011



## Contents

	Pref	ace	<i>page</i> xi
	Ackr	nowledgments	xiii
	Acro	onyms	xiv
	Note	ntion	xvi
1	Intro	oduction	1
	1.1	Motivation	1
	1.2	History and book outline	6
Part I TI	heore	etical aspects	15
2	Ran	dom matrices	17
	2.1	Small dimensional random matrices	17
		2.1.1 Definitions and notations	17
		2.1.2 Wishart matrices	19
	2.2	Large dimensional random matrices	29
		2.2.1 Why go to infinity?	29
		2.2.2 Limit spectral distributions	30
3	The	Stieltjes transform method	35
	3.1	Definitions and overview	35
	3.2	The Marčenko–Pastur law	42
		3.2.1 Proof of the Marčenko–Pastur law	44
		3.2.2 Truncation, centralization, and rescaling	54
	3.3	Stieltjes transform for advanced models	57
	3.4	Tonelli theorem	61
	3.5	Central limit theorems	63
4	Free	probability theory	71
	4.1	Introduction to free probability theory	72
	4.2	R- and $S$ -transforms	75
	4.3	Free probability and random matrices	77
	4.4	Free probability for Gaussian matrices	84

	4.5	Free probability for Haar matrices	87
5	Con	nbinatoric approaches	95
	5.1	The method of moments	95
	5.2	Free moments and cumulants	98
	5.3	Generalization to more structured matrices	105
	5.4	Free moments in small dimensional matrices	108
	5.5	Rectangular free probability	109
	5.6	Methodology	111
6	Det	erministic equivalents	113
	6.1	Introduction to deterministic equivalents	113
	6.2	Techniques for deterministic equivalents	115
		6.2.1 Bai and Silverstein method	115
		6.2.2 Gaussian method	139
		6.2.3 Information plus noise models	145
		6.2.4 Models involving Haar matrices	153
	6.3	A central limit theorem	175
7	Spe	ctrum analysis	179
	7.1	Sample covariance matrix	180
		7.1.1 No eigenvalues outside the support	180
		7.1.2 Exact spectrum separation	183
		7.1.3 Asymptotic spectrum analysis	186
	7.2	Information plus noise model	192
		7.2.1 Exact separation	192
		7.2.2 Asymptotic spectrum analysis	195
8	Eige	en-inference	199
	8.1	G-estimation	199
		8.1.1 Girko G-estimators	199
		8.1.2 G-estimation of population eigenvalues and eigenvectors	201
		8.1.3 Central limit for G-estimators	213
	8.2	Moment deconvolution approach	218
9	Ext	reme eigenvalues	223
	9.1	Spiked models	223
		9.1.1 Perturbed sample covariance matrix	224
		9.1.2 Perturbed random matrices with invariance properties	228
	9.2	Distribution of extreme eigenvalues	230
		9.2.1 Introduction to the method of orthogonal polynomials	230
		9.2.2 Limiting laws of the extreme eigenvalues	233
	9.3	Random matrix theory and eigenvectors	238

10	Summary and partial conclusions	243
Part II	Applications to wireless communications	249
11	Introduction to applications in telecommunications	251
	11.1 Historical account of major results	251
	11.1.1 Rate performance of multi-dimensional systems	252
	11.1.2 Detection and estimation in large dimensional systems	256
	11.1.3 Random matrices and flexible radio	259
12	System performance of CDMA technologies	263
	12.1 Introduction	263
	12.2 Performance of random CDMA technologies	264
	12.2.1 Random CDMA in uplink frequency flat channels	264
	12.2.2 Random CDMA in uplink frequency selective channels	273
	12.2.3 Random CDMA in downlink frequency selective channels	281
	12.3 Performance of orthogonal CDMA technologies	284
	12.3.1 Orthogonal CDMA in uplink frequency flat channels	285
	12.3.2 Orthogonal CDMA in uplink frequency selective channels	285
	12.3.3 Orthogonal CDMA in downlink frequency selective channels	286
13	Performance of multiple antenna systems	293
	13.1 Quasi-static MIMO fading channels	293
	13.2 Time-varying Rayleigh channels	295
	13.2.1 Small dimensional analysis	296
	13.2.2 Large dimensional analysis	297
	13.2.3 Outage capacity	298
	13.3 Correlated frequency flat fading channels	300
	13.3.1 Communication in strongly correlated channels	305
	13.3.2 Ergodic capacity in strongly correlated channels	309
	13.3.3 Ergodic capacity in weakly correlated channels	311
	13.3.4 Capacity maximizing precoder	312
	13.4 Rician flat fading channels	316
	13.4.1 Quasi-static mutual information and ergodic capacity	316
	13.4.2 Capacity maximizing power allocation	318
	13.4.3 Outage mutual information	320
	13.5 Frequency selective channels	322
	13.5.1 Ergodic capacity	324
	13.5.2 Capacity maximizing power allocation	325
	13.6 Transceiver design	328
	13.6.1 Channel matrix model with i.i.d. entries	331
	13.6.2 Channel matrix model with generalized variance profile	332

Contents

vii

14	Rate performance in multiple access and broadcast channels	335
	14.1 Broadcast channels with linear precoders	336
	14.1.1 System model	339
	14.1.2 Deterministic equivalent of the SINR	341
	14.1.3 Optimal regularized zero-forcing precoding	348
	14.1.4 Zero-forcing precoding	349
	14.1.5 Applications	353
	14.2 Rate region of MIMO multiple access channels	355
	14.2.1 MAC rate region in quasi-static channels	357
	14.2.2 Ergodic MAC rate region	360
	14.2.3 Multi-user uplink sum rate capacity	364
15	Performance of multi-cellular and relay networks	369
	15.1 Performance of multi-cell networks	369
	15.1.1 Two-cell network	373
	15.1.2 Wyner model	376
	15.2 Multi-hop communications	378
	15.2.1 Multi-hop model	379
	15.2.2 Mutual information	382
	15.2.3 Large dimensional analysis	382
	15.2.4 Optimal transmission strategy	388
16	Detection	393
	16.1 Cognitive radios and sensor networks	393
	16.2 System model	396
	16.3 Neyman–Pearson criterion	399
	16.3.1 Known signal and noise variances	400
	16.3.2 Unknown signal and noise variances	406
	16.3.3 Unknown number of sources	407
	16.4 Alternative signal sensing approaches	412
	16.4.1 Condition number method	413
	16.4.2 Generalized likelihood ratio test	414
	16.4.3 Test power and error exponents	416
17	Estimation	421
	17.1 Directions of arrival	422
	17.1.1 System model	422
	17.1.2 The MUSIC approach	423
	17.1.3 Large dimensional eigen-inference	425
	17.1.4 The correlated signal case	429
	17.2 Blind multi-source localization	432
	17.2.1 System model	434
	17.2.2 Small dimensional inference	436

	Contents	ix
	17.2.3 Conventional large dimensional approach	438
	17.2.4 Free deconvolution approach	440
	17.2.5 Analytic method	447
	17.2.6 Joint estimation of number of users, antennas and powers	469
	17.2.7 Performance analysis	471
18	System modeling	477
	18.1 Introduction to Bayesian channel modeling	478
	18.2 Channel modeling under environmental uncertainty	480
	18.2.1 Channel energy constraints	481
	18.2.2 Spatial correlation models	484
19	Perspectives	501
	19.1 From asymptotic results to finite dimensional studies	501
	19.2 The replica method	505
	19.3 Towards time-varying random matrices	506
20	Conclusion	511
	References	515
	Index	537