

Contents

1	Introduction	1
2	Power considerations at multi-port antennas	5
2.1	Earlier work	6
2.2	Eigenmode description of lossless arrays	8
2.2.1	Single-port antenna matching efficiency	8
2.2.2	Generalisation to multi-port antennas	10
2.2.3	The fundamental modes of radiation	14
2.2.4	Reflections of eigenmodes	16
2.3	Eigenmode far-field patterns	18
2.3.1	Far-field patterns and the radiation matrix	18
2.3.2	Beam-pattern orthogonalisation	22
2.4	Non-distinct eigenefficiencies	25
2.5	Ohmic array losses	26
2.6	An equivalent circuit for lossless arrays	27
2.7	Examples of the consequences of radiator coupling	30
2.7.1	Analysis of a manufactured $\lambda_0/10$ three-port array	30
2.7.2	Influence of number of radiators and separation	41
2.8	Summary	43
3	Decoupling and matching networks	45
3.1	General conditions for decoupling and matching	46
3.2	Decoupling by eigenmode excitation	48
3.3	Directional couplers as decoupling networks	51
3.3.1	Example: symmetric two-port antenna array	51

3.3.2	Example: symmetric three-port antenna array	52
3.4	A systematic design procedure for decoupling networks . . .	54
3.4.1	Two-element decoupling	55
3.4.2	Decoupling across a symmetry plane	57
3.4.3	Radiator merging	59
3.4.4	Eigenmode matching	63
3.5	Efficiency considerations	64
3.6	Example implementations	67
3.6.1	Linear $\lambda_0/4$ three-port array	67
3.6.2	LTCC implementation of a three-port DMN	74
3.6.3	Broadband matched two-port array	78
3.6.4	Circular $\lambda_0/10$ four-port array	85
3.7	Summary	88
4	Diversity reception with compact antenna arrays	91
4.1	Overview and past work	92
4.2	Figures of merit for correlated fading	94
4.2.1	A simplified diversity model	95
4.2.2	Array gain of a mutually coupled array	101
4.2.3	Diversity gain over a single receive antenna	102
4.2.4	Diversity loss over an ideal antenna array	105
4.3	Extensions to the diversity model	110
4.3.1	Influence of the communications environment	111
4.3.2	Effects of a decoupling and matching network	114
4.3.3	Spatially coloured receiver noise	116
4.4	A complete receiver model	118
4.4.1	Antenna array noise	122
4.4.2	Network noise	122
4.4.3	Front-end amplifier noise	124
4.4.4	Discussion of the front-end model	125
4.5	Summary	131
5	Compact antenna arrays in practice: a diversity receiver	135
5.1	Overview of the diversity system	136
5.1.1	The transmitter	137
5.1.2	The receiver front-end	143
5.1.3	Baseband processing	147

5.1.4	The graphical user interface	150
5.2	Benefits of decoupling and matching networks	152
5.3	Verification of the diversity figures of merit	157
5.4	Measurements of the signal envelope covariance matrix . . .	163
5.5	Front-end noise characterisation	168
5.5.1	Noise characterisation of a single receiver-branch . .	170
5.5.2	Noise characterisation of the multi-port receiver . . .	174
5.5.3	Influence of noise on the SNR diversity gain	179
5.6	Summary	188
6	Summary and outlook	191
7	Zusammenfassung und Ausblick	197
A	Proofs and derivations	205
A.1	<i>Diagonalisation of eigen-reflections</i>	205
A.2	Ohmic eigenefficiencies and DMNs	206
A.3	Matrix-form of a single-port matching network	207
A.4	Matrix-form of a decoupling and matching network	209
A.5	Eigenmodes fade independently	213
A.6	Series expansion of the diversity gain	215
B	Waves, scattering parameters, and noise	219
B.1	Scattering parameters	221
B.1.1	Definition	221
B.1.2	Interconnection of multi-port junctions	222
B.1.3	Renormalisation	225
B.2	Noise wave description	227
	Bibliography	231
	Notation and abbreviations	247