

# Glossary

$(\cdot)^*$	Conjugate operator
$(\cdot)^T$	Transpose operator
$(\cdot)^H$	Conjugate—transpose operator
$(\cdot)^{-1}$	Inversion operator
$(\cdot)^+$	$\max(0, \cdot)$
$\ \cdot\ _F$	Frobenius norm
$ \cdot _L$	Lebesgue measure
$\lceil \cdot \rceil$	Returns the smallest integer that is larger than the argument
$j$	Imaginary unit ( $j^2 = -1$ )
$\otimes$	Kronecker product
$\odot$	Hadamard product
$\det(\cdot)$	Determinant of a matrix
$rank(\cdot)$	Rank of a matrix
$diag(\cdot)$	Diagonal matrix
$tr(\cdot)$	Trace of a matrix
$E[\cdot]$	Mean value operator
$M_T$	Number of transmit antenna elements of a conventional MIMO system
$M_R$	Number of receive antenna elements of a conventional MIMO system
$\lambda$	Wavelength
$\xi_i$	$i$ th eigenvalue of a matrix in descending order
$\sigma_i$	$i$ th singular value of a matrix in descending order
$\sigma_{\mathbf{H}}^2$	Variance of the entries in matrix $\mathbf{H}$
$\sigma_n^2$	Noise variance
$\gamma_{bs}$	Mean SNR value of BS-MIMO systems
$\gamma_{conv}$	Mean SNR value of conventional MIMO systems
$\mathbf{I}_M$	$(M \times M)$ unity matrix
$\mathbf{H}$	MIMO transfer matrix
$r$	Number of nonzero singular values of matrix $\mathbf{H}$
$\Sigma$	Diagonal matrix that contains the $r$ nonzero singular values of the matrix $\mathbf{H}$ in descending order

<b>U</b>	Matrix that contains the left eigenvectors of $\mathbf{H}\mathbf{H}^H$
<b>V</b>	Matrix that contains the left eigenvectors of $\mathbf{H}^H\mathbf{H}$
<b>s</b>	Vector of transmit symbols
$\tilde{\mathbf{s}}$	Vector of transmit symbols, processed by a transformation matrix
<b>y</b>	Vector of received symbols
$\tilde{\mathbf{y}}$	Vector of received symbols, processed by a transformation matrix
<b>n</b>	Noise vector
$N_0$	Noise power density
$T_S$	Symbol period
$B$	Bandwidth
$C$	MIMO capacity in bps/Hz
$\mathbf{R}_{\mathbf{xx}}$	Covariance of the vector $\mathbf{x}$
$P_T$	Total transmit power
$\Lambda$	Diagonal matrix after eigenvalue decomposition of $\mathbf{H}\mathbf{H}^H$
<b>Q</b>	Unitary matrix after eigenvalue decomposition of $\mathbf{H}\mathbf{H}^H$
$C_e$	Ergodic capacity in bps/Hz
$C_{out}$	Outage capacity in bps/Hz
$Q(t)$	Time variable number of multipaths
$\Omega_{T,R,i}$	Direction of departure/arrival of a multipath component
$\mathbf{a}_{T,R}$	Transmit/receive array manifold vector
$\mathbf{R}_H$	Covariance matrix of the matrix $\mathbf{H}$
$\mathbf{R}_{T,R}$	Transmit/receive signal correlation matrix
$L_{T,R}$	Antenna linear aperture, normalized to the wavelength
$T_m$	Set of multipath components with directions of departure within the $m$ th orthonormal eigenpattern
$R_m$	Set of multipath components with directions of arrival within the $m$ th orthonormal eigenpattern
$M_{esp}$	Number of ESPAR elements (including the active)
<b>X</b>	ESPAR loading matrix
<b>Z</b>	ESPAR admittance matrix
<b>i</b>	Currents of ESPAR elements
$\tilde{d}_{ij}$	Distance between the $i$ th and $j$ th antenna elements, normalized to the wavelength
$D$	Antenna element's length, normalized to the wavelength
$d$	Radius of a circular ESPAR antenna
$\theta$	Elevation angle
$\phi$	Azimuth angle
$c_{var}$	Varactor diode's capacitance
$N_{eff}$	Number of effective aerial degrees of freedom of an ESPAR antenna
$\mathbf{B}_{T,R}$	Matrix, whose columns contain azimuth samples of the transmit/receive basis patterns
$\varphi_i$	Vector with azimuth samples of the $i$ th ESPAR basis pattern $\Phi_i(\theta, \varphi)$
$\mathbf{H}_{bs}$	BS-MIMO channel matrix
$\mathbf{H}_{conv}$	Channel matrix of a conventional MIMO system

$\mathbf{C}_{T,R}$	Transmit/receive coupling matrix of a conventional MIMO system
$Q_e$	Q factor of an antenna element
$Q_{array}$	Q factor of an antenna array
$P(\theta, \varphi)$	ESPAR radiation pattern
$D(\theta, \varphi)$	Directive gain
$B_n(\theta, \varphi)$	$n$ th ESPAR basis pattern
$E_\nu(\cdot)$	$n$ th order Weber function
$I_\nu(\cdot)$	Modified Bessel function of the first kind and $\nu$ th order
$J_\nu(\cdot)$	Bessel function of the first kind and $\nu$ th order
$\Gamma(\cdot)$	Gamma function

# Index

## A

- Adjacent channel interference, 119, 131, 134–135
- Aerial modulation, 53, 64, 96
- Algorithms
  - adaptive algorithms, 8
  - Alamouti, 89, 112
  - BLAST, 11
  - direction finding, 4
  - ESPRIT, 23
  - MUSIC, 23, 42
  - optimization cycles, 95, 97, 98
  - simultaneous perturbation stochastic approximation (SPSA), 97
  - smoothing technique, 95
  - steepest descent, 95
  - target localization, 1
- Aliasing, 121, 123, 124, 130, 136, 139
- Angular speed, 121, 123, 142, 143
- Antennas
  - active element, 2, 47, 62, 104, 146, 189, 203, 211, 223
  - antenna efficiency, 27, 33, 54, 65, 74, 128, 129, 153, 163, 198, 202, 204, 205, 209, 211, 212, 214, 218–220, 222, 223
  - antenna impedance, 24–26, 68, 100, 104, 125–127, 151, 202, 204, 230
  - antenna ports, 24, 31, 33, 199
  - antenna state, 101, 103, 105, 106, 157, 163
  - cross polarization, 29
  - current, 4, 24, 40, 52, 65, 108, 125, 144, 146, 168, 204, 222, 224
  - design, 22–26, 30, 31, 33, 37, 39, 42, 44, 46, 115, 162, 166, 168, 189, 219, 226–233
  - dipole, 25, 26, 29, 39, 143–145, 198
  - directional antennas, 28, 38
  - directivity, 28, 30, 31, 128, 172
  - EA radiators, 8, 27–31
  - elements, 1–6, 9, 11, 12, 16, 22, 24, 31–33, 36–38, 40, 43, 45–48, 50, 51, 53, 60, 61, 64, 65, 68, 74, 87, 89, 100–103, 107, 110, 111, 113, 114, 119, 120, 123, 125, 126, 128, 145–147, 150, 151, 152, 154, 156, 173, 178, 199–204, 211, 218–221, 223–227, 229, 231
  - imaginary antenna, 204, 211
  - inter-element spacing, 38, 43, 125, 189
  - isotropic antennas, 28
  - matching efficiency, 27, 106
  - microstrip, 154, 158, 160, 201
  - minimum scatterer, 100
  - mutual coupling, 4, 12, 24, 31–33
  - omni directional antennas, 28, 39, 132, 179, 180
  - patch antennas, 30, 31, 120, 201
  - planar antennas, 154, 166, 190–192, 194
  - planar inverted-F antennas (PIFA), 166, 220, 231
  - radiated power, 26–29, 31, 64, 90, 191
  - radiation efficiency, 27, 28, 31, 163, 168, 191
  - radiation resistance, 24, 26
  - reactive antenna, 126, 127, 155, 157, 171
  - realistic antenna elements, 150, 162
  - reflection coefficient, 152, 225
  - resonant frequency, 201
  - return loss, 25–27, 163
  - rotating antenna, 120–126, 132–136, 138, 139, 141, 143, 144, 146, 147
  - smart, 2, 4, 21–24, 28, 39, 40, 42, 91, 201, 220

**Antennas (cont.)**

- steering, 3, 56, 115, 203
- super-resolution analysis, 4
- weakly correlated antennas, 6, 232, 233
- Yagi-Uda, 2, 6, 38, 202
- Antennas arrays, 1–17, 21–44, 46–51, 56, 77, 86, 97, 101, 104, 106, 114, 146, 149–168, 171, 172, 178, 182, 188–194, 199, 217, 220
  - analog antenna arrays, 2–3
  - antenna selection, 217
  - antenna subarray formation, 46
  - array geometry, 48, 146
  - Buttler matrices, 50
  - digital antenna arrays, 3–5
  - distributed arrays, 14
  - manifold vector, 48, 49, 104
  - MIMO arrays, 2, 5–6, 12, 38, 43, 123, 134, 166
  - RF-preprocessing, 46
  - smart antenna arrays, 2, 39
  - steering matrix, 123
  - uniform circular arrays (UCA), 223
  - uniform linear antenna arrays (ULA), 48, 49, 205
- Azimuthal plane, 58, 63

**B**

- Bandwidth, 6, 11, 24, 25, 33, 120, 122, 127, 128, 131, 132, 134, 139, 142, 154, 163, 172, 173, 189, 201, 219, 229–231
- Bandwidth expansion, 120, 131
- Baseband signal, 4, 9, 23, 160, 160, 174–176, 178
- Beam
  - beamforming, 4, 5, 9, 11, 16, 17, 47, 52, 55, 56, 59, 62, 63, 87, 91–93, 149, 156, 172, 194, 216–219
  - beam nulling, 201
  - beam pattern, 6, 35, 74, 167, 172
  - beam shaping, 8, 93
  - beam steering, 4, 22, 56, 59, 74
  - beam switching, 40, 194
- Beamspace, 45–81, 86, 87, 89–99, 101, 106, 107, 111–113, 149–168
- Beamspace-time matrix, 89
- Binary-phase-shift-keyed (BPSK), 43, 87, 89, 94, 100, 101, 103–106, 108, 112, 114, 155, 167, 172, 173, 178, 190
  - transmission, 87
- BPSK. *See* Binary-phase-shift-keyed (BPSK)

**C**

- Coaxial feed, 154, 163
- Cognitive radio
  - cognitive scenario, 188
  - primary base station (PBS), 182, 184–188
  - primary receiver, 183–185, 187–188
  - primary transmitter, 184, 185, 187
  - spatial interweave, 181
  - spatial overlay, 181
  - spatial underlay, 172, 181
- COMP. *See* Cooperative Multipoint (CoMP)
- Comparator, 178, 179
- Cooperative Multipoint (CoMP), 14, 16
- Correlation coefficient, 68, 94, 211
- Cross-correlation, 24, 145, 203
- Cross-polar discrimination factor (XPD), 46
- CROWN project, 172
- CST Microwave Studio, 153

**D**

- Data stream, 5, 14, 73, 76, 87, 173
- Degrees of freedom (DoF), 45–81, 101, 104, 129, 130, 136, 154, 158, 225, 229
- Demonstrator, 150
- DoF. *See* Degrees of freedom (DoF)
- Doppler effect, 119, 131

**E**

- Electromagnetic
  - electromagnetic design, 150
  - electromagnetic modeling, 154, 171, 230, 232
  - electromagnetic waves, 4, 24, 26, 27, 29, 38, 230
  - full-wave electromagnetic simulation, 152, 156, 198, 199, 230, 232

**F**

- Fourier
  - components, 123–127, 130, 136, 138–143, 147
  - series, 122
- Frequency multiplexing, 119, 123

**G**

- GPS receiver, 173
- Gram-Schmidt orthogonalization, 56, 77
- Green communications, 17
- Ground plane, 29, 154, 158, 161, 166, 232

**H**

## Hardware

- ADC/DAC, 4
- control network, 98
- digital signal processing (DSP), 4
- down-conversion, 4
- feeding network, 33, 40, 98
- handheld devices, 155
- handheld terminal, 166
- hardware complexity, 45–47, 69, 79, 218, 233
- hardware constraints, 16
- hardware modules, 174
- hardware prototypes, 17
- low-pass filter, 160
- MEMS switches, 157
- PIN, 201
- printed circuit board (PCB), 176
- reconfigurable load structure, 150
- RF chain, 46, 47, 69
- RF feed, 39
- RF front ends, 175
- SMD components, 162
- super heterodyne receiver, 22
- transceiver, 45, 47, 79, 201
- up-conversion, 4
- varactor, 69, 155
- voltage source, 4

**I**

IE3D, 189, 190, 230, 232

## Impedance

- impedance matrix, 31, 32, 42, 68, 100, 104, 126, 199, 203, 209, 210, 216, 222, 224, 230, 232
  - impedance mismatch, 25, 168, 201
  - input impedance, 25, 32, 177, 204
- Impedance loads, 41, 68, 151, 153, 161, 161, 204
- circuitry, 161
  - complex, 92–93, 153
  - exhaustive search, 216
  - imaginary antenna, 41, 160, 202, 210, 216
  - implementation, 153
  - measurement, 153, 161
  - modeling, 153
  - optimization, 154
  - reactive antenna, 160
  - reactive load, 151, 160
  - reconfigurable, 41, 160
  - states, 41, 161
  - variable load design, 151, 161

Information stream, 5

Inter-symbol interference, 34–35

**K**

Kronecker model, 68, 205, 220

**L**

Long term evolution (LTE), 14, 172, 188–194, 213

testbed, 172

LTE. *See* Long term evolution (LTE)**M**

Matlab, 128, 189, 216, 226, 232

MIMO. *See* Multiple input/multiple output (MIMO)

MMDS frequencies (2,500–2,700 MHz), 172

Mobile communication, 42, 166, 188

Mode voltages, 101, 102

Multiple input/multiple output (MIMO)

massive MIMO, 15–16

MIMO links, 5, 6, 9–13, 37

MIMO networks, 13–16

MIMO transmission, 5, 11, 42, 88–114,

150, 154, 156, 171, 172, 178–181, 202

multi-antenna communication, 5

multi-antenna receiver, 9

multi-antenna transmitter, 9

multiplexing gain, 11, 12, 45, 115, 141,

147, 202, 207

spatial modes, 5, 89

spatial multiplexing, 5, 6, 11, 12, 47, 105,

123, 172, 202

testbed, 172–174

waterfilling, 11, 111

Multiplexing order, 67, 86, 97, 105, 106

## Multiuser networks

backhaul h/w, 14

base station, 13

broadband networks, 17

broadcast channel, 13

cellular networks, 12–14

co-channel cells, 14

downlink, 13, 14

femtocells, 16

forward link, 13

frequency reuse, 14

interference, 5, 11, 14, 15

interference alignment, 15

interference cancellation, 45

mobile terminals, 12, 13

### Multiuser networks (*cont.*)

- multi-antenna wireless networking, 16
- multi-user detection, 4
- multiuser networks, 198
- reverse link, 13
- SDMA, 4, 23
- sectorization, 12
- sectors, 13
- sensor networks, 17
- successive interference cancellation, 11
- uplink, 13, 14
- wireless networks, 17, 33–36

### N

- Noise cross-correlation, 145

### O

- On-off keying (OOK), 88, 89
- Orthogonal basis, 56, 67, 71, 78, 88, 101, 110, 167, 173

### P

- Packet data, 14
- Parasitic antennas
  - active circuit block, 91, 92
  - adaptive loads, 8
  - admittance matrix, 65, 100, 101
  - analogue control circuits, 21–23
  - basis patterns, 53, 54, 56–63, 78, 90, 92, 94, 101, 103, 107, 167
  - beam-space, 47, 51, 54–63, 77, 86, 87, 90–93, 101, 106, 107, 112, 149–168
  - characteristic impedance, 222, 229, 232
  - correction factor, 107, 108
  - correlation matrix, 220, 222, 226
  - coupling matrix, 42
  - decoupling, 229
  - design, 22–27, 30, 31, 33, 34, 38–42, 44, 86, 115, 149–168, 172, 188–194
  - DMN, 112, 219, 229
  - effective coupling, 41, 52
  - 3 element ESPAR, 104, 178, 180, 181, 194
  - 5 element ESPAR, 56, 66, 67, 74, 194
  - ESPAR, 8, 41, 42, 52, 54–56, 58, 87, 91–92, 107, 188, 194
  - feeding network, 33, 40, 98
  - implementation, 32, 38, 120, 123, 149–168
  - individual port matching, 87
  - inter-element distance, 17, 33, 41, 47, 74, 125, 129, 130, 189
  - matching networks, 166

- measurement, 153, 154, 157–163
- multiport conjugate matching, 201
- mutual coupling, 2, 24, 31–33, 38–42, 125, 127, 128
- mutual impedance matrix, 100, 104
- parasitic antenna array design, 149–168, 172, 189–194
- parasitic antenna arrays, 2, 6–9, 17, 21–44, 47, 77, 86, 97, 104, 106, 171, 172, 188–194
- parasitic elements, 2, 8, 39–42, 47, 58, 59, 120, 123, 125, 172, 188, 189
- parasitic loads, 41, 93, 94
- power imbalance, 154, 167, 168
- reactance, 52, 56, 104, 107, 153, 155–157, 160, 198
- reactive loads, 52, 126–128, 130, 150–152, 154–159, 160, 162
- single RF front end, 42, 173
- switching circuits, 6, 41
- switch parasitic arrays, 7, 39, 40, 88, 198, 218
- wave-vector domain, 44, 173

PARC. *See* Per-antenna-rate-control (PARC)

### Pattern

- antenna pattern rotation, 120, 121, 123, 127, 130, 136, 139, 141–143
- array broad side, 3
- basis patterns, 49, 52–65, 67, 70–81, 87, 88, 90–92, 94, 101, 103, 105–107, 109–112, 115, 116, 167
- cardioid patterns, 87–90
- 3D radiation pattern, 3, 194
- embedded radiation patterns, 151
- far-field, 2, 43, 47, 56–59, 63, 64, 70, 71, 92, 101, 104–107
- imbalanced basis patterns, 101, 111
- isolated element patterns, 100, 102, 103
- pattern coefficient matrix, 123
- pattern mapping, 53
- pattern modulation, 64
- port beam patterns, 112
- radiation field, 2
- radiation pattern, 2, 3, 6, 8, 28, 30, 31, 34–36, 38–43, 51–54, 56, 57, 63, 65–67, 94, 101, 104, 109, 113, 114, 150–153, 162, 168, 189, 192, 199, 232

Per-antenna-rate-control (PARC), 11

### Performance metrics

- aerial degrees of freedom, 47, 56–63, 101, 104
- array gain, 45

- battery saving, 16
- diversity, 17, 42, 46, 87, 89, 90, 112–114, 124, 167, 198, 201, 202, 217–232
- diversity gain, 8, 13, 45, 112, 202, 218
- ergodic capacity, 10, 11, 68, 69, 77, 78, 92, 112, 128–130, 206, 207, 209, 210, 214, 216
- hardware savings, 46, 47, 69
- multiuser diversity, 17, 198, 217–233
- mutual information, 10, 128, 129, 131, 133, 134, 138, 139, 141, 142, 144, 145
- open loop capacity, 10, 11, 106, 207
- outage capacity, 69, 70, 87, 102, 103, 106, 107, 111, 205, 207
- peak rate, 12, 14, 16
- power dissipation, 5, 6
- QoS, 12
- signal to noise and interference ratio (SINR), 12, 184–186, 188
- signal-to-noise ratio (SNR), 11, 55, 68, 69, 76, 77, 103, 106, 111, 112, 129–132, 134, 146, 147, 164, 180, 184–187, 207, 209, 210, 213–217, 220, 225
- spatial selectivity, 3
- spectral efficiency, 5, 10, 14, 24, 46, 47, 67, 86, 104, 110, 180
- sum-rate capacity, 13, 14
- throughput, 198, 213, 217, 225–229, 233
- Processing
  - baseband processing, 5, 23
  - digital processing, 2, 3, 8, 12
  - digital signal processing, 4–6, 9, 14, 22, 23, 40–42, 174–176, 178
  - signal processing, 3, 4, 17, 23, 24, 28, 36, 42, 44–46, 176, 189
  - space-time processing, 40, 45
  - spatial processing, 8, 14
- Proof-of-concept, 150, 169, 171–194
- Prototype, 17, 150, 154, 162, 163
- Pulse shaping, 123, 132, 157, 160
  
- R**
- Radio frequency (RF), 4–6, 8, 9, 17, 21, 23, 39, 40, 42, 45–47, 51–56, 63–70, 78, 79, 86–115, 155–157, 172–181, 194, 200–202, 210, 218, 220, 222, 223, 225, 229, 230, 232
  - signals, 4, 23, 101, 176, 177
- Reconfiguration, 70, 76, 155, 158
- Remote radio heads, 17
- Resistance, 24, 26, 92, 144, 160, 162
- RF. *See* Radio frequency (RF)
  
- S**
- Sampling, 23, 47–50, 52, 53, 71–73, 119, 120, 124, 130, 131, 133, 135–143, 182
  - over-sampling, 54, 55, 68, 69, 120, 139, 147
  - under-sampling, 139, 141–142
- Scheduler, 12
- SEMCAD, 153
- Sensing, 17, 156
- Sensors, 6, 9, 16, 17, 206
- Signal space, 51, 56, 57, 205
- Signal waveforms, 57
- SIMO, 220
- Singular value decomposition (SVD), 11, 37, 63, 72, 73, 78
- SISO, 11, 12, 68–70, 93, 166
- Spatial domain, 23, 45, 47–50, 112, 182
- Specific absorption rate (SAR), 166, 168
- Spectral copies, 122, 136, 140, 143
- Spherical surface, 71
- Spurious resonance, 160
- SVD. *See* Singular value decomposition (SVD)
- Switching
  - SAS, 87, 103, 106, 107
  - SPA, 107, 162, 163, 173, 178, 181
  
- T**
- Training sequence, 173, 178, 180
- TRL calibration, 160, 161
  
- W**
- Wavelength, 4, 6, 9, 12, 29, 30, 38, 49, 58, 59, 67, 130, 156
- WiFi, 16
- Wireless channel
  - AoA, 21, 22, 34, 35, 42, 48, 49, 67, 72, 115
  - AoD, 34, 35, 48, 49, 67, 72, 115, 203, 209, 211, 213
  - azimuthal angle, 2, 3
  - channel estimation, 16, 72
  - channel matrix, 10, 11, 38, 48, 49, 51–54, 71–73, 76, 94, 102, 110, 111, 123, 126, 129, 132, 133, 206, 220
  - clustered channel model, 67
  - delay spread, 35
  - elevation angle, 2, 3, 59, 63, 192
  - flat fading, 35, 37, 205, 207
  - impulse response, 11, 34, 35
  - incident waves, 22, 33
  - interference channel, 14, 15, 144
  - keyhole channel, 12



**Wireless channel** (*cont.*)

    multipath, 34–36, 48, 49, 70, 115  
    multiple access channel, 13  
    polarization, 27–31, 38, 46, 166  
    power azimuth spectrum (PAS), 67,  
        201–204, 209, 216, 222, 224, 227  
    propagation channel, 5, 46, 51, 54, 70, 76,  
        138, 200, 217, 233  
    Rayleigh i.i.d. fading, 10  
    rich scattering, 12, 67, 70, 145, 146, 211  
    rms delay spread, 35  
    scattering response, 51  
    spatial zooming, 50  
    virtual channel matrix, 48, 49, 52, 71–73

    wave scattering theory, 51

    WINNER channel models, 74

Wireless communication, 1, 6, 9, 17, 27, 33,  
    36, 40, 42, 219

Wireless sensors, 16

**X**

XPD. *See* Cross-polar discrimination factor  
(XPD)

**Z**

Zero-forcing, 178, 180, 207, 208, 217