

## Table of Contents

<b>Notations</b> . . . . .	xiii
<b>Acknowledgments</b> . . . . .	xv
<b>Introduction</b> . . . . .	xix
<b>Chapter 1. Overview</b> . . . . .	1
1.1. Introduction . . . . .	2
1.2. Quantum information . . . . .	4
1.2.1. Principles . . . . .	5
1.2.2. Imperfect quantum systems . . . . .	7
1.2.3. Quantum computers . . . . .	8
1.2.4. Applications of distributed quantum information . . . . .	9
1.3. Quantum repeaters . . . . .	10
1.3.1. Physical communication technologies . . . . .	11
1.3.2. Multi-hop Bell pairs: quantum communication sessions . . . . .	12
1.4. Network architectures . . . . .	15
1.4.1. Semantics of distributed quantum information . . . . .	16
1.4.2. Identifiers . . . . .	17
1.4.3. Paths . . . . .	17
1.4.4. Resource management discipline . . . . .	18
1.4.5. A quantum internet . . . . .	20
1.5. Conclusions . . . . .	20

<b>PART 1. FUNDAMENTALS</b> . . . . .	23
<b>Chapter 2. Quantum Background</b> . . . . .	25
2.1. Introduction . . . . .	26
2.2. Schrödinger's equation . . . . .	28
2.3. Qubits . . . . .	29
2.3.1. What is a qubit? . . . . .	29
2.3.2. Quantum registers and weighted probabilities . . . . .	30
2.3.3. Interference . . . . .	32
2.3.4. Entanglement . . . . .	33
2.3.5. Decoherence . . . . .	34
2.3.6. Pure and mixed states and the density matrix . . . . .	34
2.3.7. Fidelity . . . . .	37
2.3.8. Measurement . . . . .	38
2.3.9. The partial trace . . . . .	39
2.4. Manipulating qubits . . . . .	41
2.4.1. What is a quantum gate? . . . . .	41
2.4.2. Single-qubit gates and the Bloch sphere . . . . .	41
2.4.3. Global versus relative phase . . . . .	44
2.4.4. Two-qubit gates . . . . .	45
2.4.5. Quantum circuits . . . . .	46
2.5. Bell pairs . . . . .	47
2.5.1. The Bell basis . . . . .	49
2.5.2. Measurement in the Bell basis . . . . .	49
2.5.3. The Bell inequalities and non-locality . . . . .	50
2.5.4. Experimental demonstration of violation of Bell's inequality . . . . .	52
2.6. The no-cloning theorem . . . . .	53
2.7. Conclusion . . . . .	54
<b>Chapter 3. Networking Background</b> . . . . .	55
3.1. Concepts . . . . .	56
3.1.1. Multihop communication: networks as graphs . . . . .	56
3.1.2. Resources . . . . .	59
3.1.3. Protocols . . . . .	60
3.1.4. Naming and addressing . . . . .	61
3.1.5. Security . . . . .	62
3.2. Challenges in scaling up networks . . . . .	63
3.2.1. Heterogeneity . . . . .	63
3.2.2. Scale . . . . .	64
3.2.3. Dealing with out-of-date information . . . . .	64
3.2.4. Organizational needs . . . . .	64
3.2.5. Misbehaving nodes . . . . .	65

3.3. Design patterns . . . . .	65
3.3.1. Hierarchy . . . . .	65
3.3.2. Layering . . . . .	66
3.3.3. Narrow waist . . . . .	67
3.3.4. Multiplexing resources . . . . .	68
3.3.5. Smart versus dumb networks . . . . .	70
3.3.6. Distributed management and autonomy . . . . .	70
3.3.7. State machines . . . . .	71
3.3.8. Weak consistency and soft failure . . . . .	72
3.3.9. Distributed routing protocols . . . . .	73
3.3.10. Overlays, virtualization and recursion . . . . .	74
3.4. The Internet . . . . .	75
3.5. Conclusion . . . . .	77
<b>Chapter 4. Teleportation . . . . .</b>	<b>79</b>
4.1. The basic teleportation operation . . . . .	79
4.2. Experimental demonstration of teleportation . . . . .	82
4.3. State machines for teleportation . . . . .	84
4.4. Teleporting gates . . . . .	86
4.5. Conclusion . . . . .	88
<b>PART 2. APPLICATIONS . . . . .</b>	<b>91</b>
<b>Chapter 5. Quantum Key Distribution . . . . .</b>	<b>93</b>
5.1. QKD and the purpose of cryptography . . . . .	94
5.2. BB84: single-photon QKD . . . . .	97
5.3. E91: entanglement-based protocol . . . . .	100
5.4. Using QKD . . . . .	101
5.4.1. Campus-to-campus virtual private network . . . . .	101
5.4.2. Transport-layer security (TLS) . . . . .	103
5.4.3. Resilience of networks dependent on QKD . . . . .	104
5.5. Existing QKD networks . . . . .	105
5.6. Classical control protocols . . . . .	109
5.7. Conclusion . . . . .	111
<b>Chapter 6. Distributed Digital Computation and Communication . . . . .</b>	<b>113</b>
6.1. Useful distributed quantum states . . . . .	114
6.1.1. The stabilizer representation . . . . .	114
6.1.2. GHZ and W states . . . . .	115
6.1.3. Graph states . . . . .	116
6.2. Coin flipping . . . . .	118
6.2.1. The simplest multi-party distributed quantum protocol . . . . .	118

6.2.2. QKD-Based protocols . . . . .	118
6.2.3. Practical, optimal quantum strong coin flipping . . . . .	119
6.3. Leader election . . . . .	119
6.3.1. The second simplest multi-party distributed quantum protocol . . . . .	120
6.3.2. Tani <i>et al.</i> 's quantum protocol . . . . .	120
6.4. Quantum secret sharing . . . . .	121
6.4.1. Semi-classical, multi-party secret creation . . . . .	121
6.4.2. The basic quantum secret sharing protocol . . . . .	122
6.4.3. Verifiable quantum secret sharing and secure multi-party quantum computation . . . . .	124
6.5. Byzantine agreement . . . . .	126
6.5.1. The original problem . . . . .	126
6.5.2. Ben-Or and Hassidim's quantum Byzantine agreement . . . . .	127
6.6. Client-server and blind computation . . . . .	128
6.7. Conclusion . . . . .	130
<b>Chapter 7. Entangled States as Reference Frames . . . . .</b>	<b>131</b>
7.1. Qubits in the environment . . . . .	131
7.1.1. Precession . . . . .	132
7.1.2. Quantum optical interference . . . . .	133
7.2. Distributed clock synchronization . . . . .	135
7.2.1. Chuang's algorithms . . . . .	135
7.2.2. Jozsa <i>et al.</i> 's clock synchronization . . . . .	138
7.2.3. Further work . . . . .	140
7.3. Very long baseline optical interferometry . . . . .	141
7.4. Conclusion . . . . .	145
<b>PART 3. LINES OF REPEATERS . . . . .</b>	<b>147</b>
<b>Chapter 8. Physical Entanglement and Link-Layer Protocols . . . . .</b>	<b>149</b>
8.1. Creating entanglement using light . . . . .	149
8.1.1. Quantum states of light . . . . .	149
8.1.2. Emission . . . . .	151
8.1.3. Transport . . . . .	152
8.1.4. Detection . . . . .	154
8.2. Memory and transceiver qubits . . . . .	156
8.2.1. Gate noise . . . . .	157
8.2.2. Single-qubit decoherence . . . . .	158
8.2.3. Two-qubit decoherence . . . . .	160
8.3. Link structure . . . . .	161
8.4. State machines and protocol interactions . . . . .	163

8.5. Managing density matrices in distributed software . . . . .	164
8.5.1. Link-Level tracking of memory . . . . .	167
8.5.2. Synchronizing higher layers . . . . .	168
8.6. Examples . . . . .	169
8.7. Conclusion . . . . .	173
<b>Chapter 9. Purification . . . . .</b>	<b>175</b>
9.1. Measurement revisited . . . . .	175
9.2. Basic purification . . . . .	177
9.2.1. Bit flip errors . . . . .	178
9.2.2. Generalizing: incorporating phase flip errors and different Bell pairs . . . . .	179
9.2.3. Multiple rounds and error redistribution . . . . .	182
9.2.4. Resource consumption in multiple rounds . . . . .	184
9.3. Scheduling purification . . . . .	185
9.4. State machines and protocol interactions . . . . .	187
9.5. More complex purification protocols . . . . .	190
9.6. Experimental demonstrations . . . . .	192
9.7. Conclusion . . . . .	193
<b>Chapter 10. Purification and Entanglement Swapping-Based Repeaters . . . . .</b>	<b>195</b>
10.1. Hardware architectures . . . . .	195
10.2. Getting from here to there . . . . .	197
10.2.1. Hop-by-hop teleportation . . . . .	197
10.2.2. Basic entanglement swapping . . . . .	200
10.2.3. Multi-hop swapping . . . . .	202
10.3. Nested purification session architecture . . . . .	203
10.3.1. Proof of polynomial resource growth . . . . .	203
10.3.2. Problems to avoid . . . . .	204
10.4. State machines and protocol interactions . . . . .	206
10.5. Putting it all together . . . . .	208
10.5.1. Simulating lines of repeaters . . . . .	209
10.5.2. Greedy algorithm . . . . .	211
10.5.3. Banded performance v. total distance . . . . .	212
10.5.4. Finding the bands . . . . .	212
10.5.5. Varying swapping thresholds . . . . .	213
10.6. Considerations in the design of a simulator . . . . .	215
10.7. Conclusion . . . . .	217
<b>Chapter 11. Quantum Error Correction-Based Repeaters . . . . .</b>	<b>219</b>
11.1. Quantum error correction . . . . .	220
11.1.1. Steane code . . . . .	221

11.1.2. Surface code . . . . .	221
11.1.3. An early communication proposal . . . . .	223
11.2. CSS repeaters . . . . .	223
11.2.1. Protocols . . . . .	225
11.2.2. Operational timing . . . . .	227
11.2.3. Resources and performance . . . . .	229
11.3. Surface code repeaters . . . . .	230
11.3.1. Protocols . . . . .	232
11.3.2. Operational timing . . . . .	233
11.3.3. Resources and performance . . . . .	234
11.4. Conclusion . . . . .	235
<b>Chapter 12. Finessing the Key Limitations . . . . .</b>	<b>237</b>
12.1. Quasi-asynchronous . . . . .	238
12.1.1. Purification replacement operation . . . . .	240
12.1.2. QEC-based operation . . . . .	241
12.1.3. Timing variants . . . . .	242
12.2. Memoryless . . . . .	244
12.3. Summary: comparing quantum communication approaches . . . . .	247
12.4. Conclusion . . . . .	251
<b>PART 4. NETWORKS OF REPEATERS . . . . .</b>	<b>253</b>
<b>Chapter 13. Resource Management and Multiplexing . . . . .</b>	<b>255</b>
13.1. Simulated network and traffic . . . . .	256
13.1.1. Network topology and simulator . . . . .	256
13.1.2. Traffic load . . . . .	258
13.1.3. Adjusting link target fidelity . . . . .	258
13.2. Simulations . . . . .	259
13.2.1. Circuit switching: upper and lower throughput bounds . . . . .	259
13.2.2. Other multiplexing disciplines . . . . .	260
13.3. Conclusion . . . . .	263
<b>Chapter 14. Routing . . . . .</b>	<b>265</b>
14.1. Introduction . . . . .	265
14.2. Difficulties: differences between quantum and classical networks . . . . .	267
14.3. Problems and solutions . . . . .	268
14.4. Simulation and results . . . . .	270
14.4.1. The behavior questions . . . . .	271
14.4.2. Simulated hardware and link costs . . . . .	271
14.4.3. Simulated path candidates . . . . .	274

14.4.4. Answering our behavior questions . . . . .	275
14.4.5. Solving our problems . . . . .	280
14.5. Conclusion . . . . .	283
<b>Chapter 15. Quantum Recursive Network Architecture . . . . .</b>	<b>285</b>
15.1. Review: network architecture . . . . .	286
15.2. Recursive quantum requests . . . . .	288
15.2.1. Processing in recursive networks . . . . .	289
15.2.2. Naming a state . . . . .	290
15.2.3. Defining quantum requests . . . . .	291
15.3. Implementing recursion in quantum networks . . . . .	294
15.3.1. Satisfying quantum requests . . . . .	294
15.3.2. Paths and rendezvous points . . . . .	294
15.4. Example . . . . .	295
15.5. Conclusion . . . . .	298
<b>Chapter 16. Coda . . . . .</b>	<b>301</b>
16.1. Future development . . . . .	301
16.1.1. Hardware . . . . .	301
16.1.2. Making QRNA real . . . . .	302
16.2. Open problems . . . . .	303
16.3. Further readings for depth . . . . .	304
16.3.1. Quantum repeaters and QKD . . . . .	304
16.3.2. Optics and general quantum physics . . . . .	304
16.3.3. Quantum computing . . . . .	304
16.4. Further readings for breadth . . . . .	305
16.4.1. Information theory . . . . .	305
16.4.2. Dense coding . . . . .	305
16.4.3. Quantum network coding . . . . .	306
16.4.4. Entanglement percolation . . . . .	306
16.5. Final thoughts . . . . .	307
<b>Bibliography . . . . .</b>	<b>309</b>
<b>Index . . . . .</b>	<b>331</b>