# Contents

**Acronyms** . . . . . ix

**Preface** . . . . . xiii

**Introduction** . . . . . xvii

**Chapter 1. Toward a Decentralized SDN Control Architecture: Overview and Taxonomy** . . . . . 1

1.1. Introduction . . . . . 1
1.2. Software-defined networking: a centralized control architecture . . . . 2
1.2.1. Conventional networking and the SDN paradigm . . . . . 2
1.2.2. The SDN architecture . . . . . 3
1.3. Physical classification of existing SDN control plane architectures . . 8
1.3.1. Physically centralized SDN control . . . . . 8
1.3.2. Physically distributed SDN control . . . . . 11
1.4. Logical classification of existing SDN control plane architectures . . . 16
1.4.1. Logically centralized SDN control . . . . . 17
1.4.2. Logically distributed SDN control . . . . . 22
1.5. Conclusion . . . . . 26

**Chapter 2. Decentralized SDN Control: Major Open Challenges** . . 27

2.1. Introduction . . . . . 27
2.2. Scalability . . . . . 28
2.2.1. Data plane extensions . . . . . 30
2.2.2. Control plane distribution . . . . . 32
2.3. Reliability . . . . . 33
2.3.1. Control state redundancy . . . . . 33
2.3.2. Controller failover . . . . . 34

2.4. Controller state consistency . . . . . 35
2.4.1. Static consistency . . . . . 36
2.4.2. Adaptive multi-level consistency . . . . . 37
2.5. Interoperability . . . . . 38
2.5.1. Interoperability between the SDN controllers . . . . . 38
2.5.2. SDN interoperability with legacy networks . . . . . 38
2.6. Other challenges . . . . . 39
2.7. Conclusion . . . . . 40

**Chapter 3. Scalability and Reliability Aware SDN Controller Placement Strategies** . . . . . 41

3.1. Introduction . . . . . 41
3.2. Related work . . . . . 42
3.3. The SDN controller placement optimization problem . . . . . 44
3.3.1. Problem statement . . . . . 44
3.3.2. Problem formulation . . . . . 45
3.3.3. Placement metrics . . . . . 45
3.4. The proposed SDN controller placement scheme . . . . . 49
3.4.1. The adopted approach . . . . . 49
3.4.2. Multi-criteria placement algorithms . . . . . 50
3.4.3. Gradual strategies . . . . . 52
3.5. Performance evaluation . . . . . 53
3.5.1. Simulation settings . . . . . 53
3.5.2. Simulation results . . . . . 54
3.6. Discussion . . . . . 60
3.7. Conclusion . . . . . 62

**Chapter 4. Adaptive and Continuous Consistency for Distributed SDN Controllers: Anti-Entropy Reconciliation Mechanism** . . . . . 65

4.1. Introduction . . . . . 65
4.2. Related work . . . . . 66
4.3. The consistency problem in SDN . . . . . 68
4.3.1. Consistency trade-offs in SDN . . . . . 68
4.3.2. Consistency models in SDN . . . . . 69
4.4. Consistency models in ONOS . . . . . 70
4.4.1. Strong consistency in ONOS . . . . . 70
4.4.2. Eventual consistency in ONOS . . . . . 71
4.5. The proposed adaptive consistency for ONOS . . . . . 72
4.5.1. A continuous consistency model for ONOS . . . . . 72
4.5.2. Our consistency adaptation strategy for ONOS . . . . . 74
4.5.3. Our implementation approach . . . . . 74
4.6. Performance evaluation . . . . . 76
4.6.1. Experimental setup . . . . . 76

4.6.2. Results . . . . . 76
4.7. Conclusion . . . . . 79

**Chapter 5. Adaptive and Continuous Consistency for Distributed SDN Controllers: Quorum-Based Replication** . . . . . 81

5.1. Introduction . . . . . 81
5.2. Background on eventual consistency in distributed data stores . . . . . 83
5.2.1. Consistency and performance metrics . . . . . 83
5.2.2. Adaptive consistency control . . . . . 84
5.2.3. Existing modern tunable consistency systems . . . . . 84
5.3. The proposed adaptive Quorum-inspired consistency for ONOS . . . . 86
5.3.1. A continuous consistency model for ONOS . . . . . 86
5.3.2. Our Quorum-inspired consistency adaptation strategy for ONOS . . . . . 87
5.4. Implementation approach on ONOS . . . . . 93
5.4.1. Design of a CDN-like application . . . . . 93
5.4.2. State synchronization and content distribution . . . . . 94
5.4.3. Content delivery to customers . . . . . 95
5.5. Performance evaluation . . . . . 97
5.5.1. Application-specific performance and consistency metrics . . . . . 97
5.5.2. Experimental setup . . . . . 98
5.5.3. Results . . . . . 103
5.6. Conclusion . . . . . 112

**Conclusions and Perspectives** . . . . . 115
C.1. Summary of contributions . . . . . 115
C.2. Perspectives and future work . . . . . 117

**References** . . . . . 121

**Index** . . . . . 139