# Contents


**1 Introduction** **1**
- 1.1 Current Trends and Issues in Mobile Access Networks . . . 1
  - 1.1.1 Increasing Data Rate Demands . . . 1
  - 1.1.2 Densification of Mobile Access Networks . . . 2
- 1.2 Scope & Goals . . . 3
- 1.3 Approaches . . . 4
  - 1.3.1 Anticipatory Download Scheduling . . . 4
  - 1.3.2 Backhaul Reconfiguration . . . 5
- 1.4 Contributions . . . 5
- 1.5 Structure of the Thesis . . . 7

**2 Technical Background** **11**
- 2.1 Backhaul Networks . . . 11
  - 2.1.1 WDM-PON . . . 12
  - 2.1.2 Power Consumption . . . 13
  - 2.1.3 Software Defined Networks . . . 13
- 2.2 Wireless Access Networks . . . 14
  - 2.2.1 Simple 3GPP Radio Model . . . 15
  - 2.2.2 GreenTouch Radio Model . . . 16
  - 2.2.3 Power Consumption . . . 17
- 2.3 Wireless Coordination . . . 18
  - 2.3.1 Coordinated Multipoint Transmission and Reception . . . 18
  - 2.3.2 Software Defined Base Station Coordination . . . 20
- 2.4 Application Layer . . . 20
  - 2.4.1 HTTP Live Streaming . . . 20
  - 2.4.2 Data Rate Prediction . . . 21

**3 State of the Art & Related Work on Anticipatory Download Scheduling** **23**
- 3.1 Smarter Phones and Networks . . . 23
- 3.2 Related Work . . . 24

**4 Anticipatory Download Scheduling with Perfect Prediction** **27**
- 4.1 Problem Description . . . 28
- 4.2 Optimal Solution . . . 29
  - 4.2.1 Model Assumptions . . . 29
  - 4.2.2 Mixed Integer Quadratically Constrained Program . . . 30
  - 4.2.3 Objective . . . 32

4.2.4 Complexity . . . 32
4.3 Fill Algorithm . . . 33
4.4 Greedy Algorithms . . . 36
4.4.1 BufferFirst Algorithm . . . 36
4.4.2 QualityFirst Algorithm . . . 37
4.5 Evaluation . . . 38
4.5.1 Scenario . . . 38
4.5.2 Results . . . 39
4.5.3 Algorithm Running Times . . . 41
4.6 Summary . . . 42

**5 Anticipatory Download Scheduling with Uncertain Prediction 43**
5.1 Problem Description . . . 44
5.2 Generic Predictor . . . 44
5.2.1 Stochastic Model of Prediction Errors . . . 45
5.2.2 Implementation . . . 45
5.3 Evaluation of Perfect Prediction Algorithms with Uncertain Predictions 46
5.3.1 Scenario . . . 46
5.3.2 Results . . . 46
5.4 Plan Algorithm . . . 49
5.5 Evaluation . . . 56
5.5.1 Comparison with Perfect Prediction Schedulers . . . 56
5.5.2 Influence of the Prediction Horizon . . . 61
5.6 Summary . . . 62

**6 Anticipatory Download Scheduling for Energy Efficiency 63**
6.1 Problem Description . . . 64
6.2 Optimal Solution . . . 65
6.2.1 OptBasic . . . 66
6.2.2 OptFlex . . . 68
6.3 Two-Phase Algorithm . . . 69
6.3.1 Quality selection phase . . . 69
6.3.2 Base station disabling phase . . . 72
6.4 Evaluation . . . 73
6.4.1 Scenarios . . . 73
6.4.2 Three BSs Scenario Results . . . 74
6.4.3 Train Scenario Results . . . 78
6.5 Summary . . . 79

**7 Anticipatory Download Scheduling Prototype 81**
7.1 System Design . . . 81
7.1.1 Design Decisions . . . 82
7.1.2 Architecture and Implementation . . . 83
7.2 Prototype Implementation . . . 84
7.2.1 Protocol Extension . . . 84
7.2.2 Testbed . . . 86

7.3 Evaluation . . . 88
7.4 Summary . . . 90

**8 State of the Art & Related Work on Backhaul Network Reconfiguration 91**
8.1 Backhaul Network Reconfiguration for CoMP . . . 91
8.2 CROWD Controller Architecture . . . 93
8.3 Related Work . . . 96

**9 Backhaul Network Reconfiguration 97**
9.1 Problem Description . . . 98
9.2 Optimal Solution . . . 99
9.2.1 Integer Linear Program . . . 99
9.2.2 Complexity . . . 102
9.3 BFS Algorithm . . . 102
9.3.1 Inputs . . . 103
9.3.2 Algorithm Implementation . . . 103
9.4 Evaluation . . . 107
9.4.1 Scenario . . . 107
9.4.2 Comparison: Optimization vs. Heuristic Algorithm . . . 108
9.4.3 Heuristic Algorithm in Large Scenarios . . . 110
9.4.4 Energy Efficiency . . . 113
9.5 Summary . . . 114

**10 Backhaul Network Reconfiguration Extension for DenseNets 115**
10.1 Problem Description . . . 116
10.2 Hotspot BFS Algorithm . . . 116
10.3 Evaluation . . . 118
10.3.1 Hotspot Scenario . . . 118
10.3.2 Hotspot Scenario Results . . . 119
10.3.3 Non-Hotspot Scenario Extended Results . . . 123
10.4 Summary . . . 127

**11 Backhaul Network Reconfiguration Prototype 129**
11.1 Architecture . . . 130
11.2 Implementation . . . 131
11.2.1 Controller and CLC Manager Plugin . . . 131
11.2.2 Backhaul Network with Maxinet . . . 133
11.2.3 Prototype Setup . . . 134
11.3 Evaluation . . . 136
11.3.1 Scenario . . . 136
11.3.2 Results . . . 136
11.4 Summary . . . 138

**12 Conclusion & Future Research Directions 139**
12.1 Discussion . . . 139

12.2 Conclusion . . . . . 140
12.3 Future Research Directions . . . . . 141

**Acronyms** **143**

**Bibliography** **145**