

# Contents

|          |                                                        |           |
|----------|--------------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction</b>                                    | <b>1</b>  |
| 1.1      | Problem Analysis . . . . .                             | 3         |
| 1.1.1    | Promises of Blockchain Technology . . . . .            | 3         |
| 1.1.2    | Problems of Blockchain-based Data Management . . . . . | 5         |
| 1.2      | Research Questions . . . . .                           | 8         |
| 1.3      | Contributions . . . . .                                | 9         |
| 1.3.1    | Attribution of Contributions . . . . .                 | 14        |
| 1.4      | Outline . . . . .                                      | 16        |
| <br>     |                                                        |           |
| <b>2</b> | <b>Bitcoin and Blockchain Technology</b>               | <b>17</b> |
| 2.1      | Bitcoin Overview . . . . .                             | 18        |
| 2.2      | Blockchain Structure . . . . .                         | 23        |
| 2.2.1    | Overview . . . . .                                     | 23        |
| 2.2.2    | Block Structure . . . . .                              | 24        |
| 2.2.3    | Merkle Trees . . . . .                                 | 27        |
| 2.3      | Transactions . . . . .                                 | 29        |
| 2.3.1    | Overview . . . . .                                     | 29        |
| 2.3.2    | Coin Ownership . . . . .                               | 31        |
| 2.3.3    | Scripting System . . . . .                             | 35        |
| 2.3.4    | Segregated Witnesses . . . . .                         | 42        |
| 2.3.5    | Managing Unspent Transaction Outputs . . . . .         | 43        |
| 2.4      | Consensus . . . . .                                    | 44        |
| 2.4.1    | Mining Process . . . . .                               | 45        |
| 2.4.2    | Distribution and Validation Process . . . . .          | 47        |

|          |                                                                   |            |
|----------|-------------------------------------------------------------------|------------|
| 2.4.3    | Forks . . . . .                                                   | 49         |
| 2.5      | Peer-to-Peer Network . . . . .                                    | 52         |
| 2.5.1    | Network Overview . . . . .                                        | 52         |
| 2.5.2    | Node Connections . . . . .                                        | 55         |
| 2.5.3    | Data Dissemination . . . . .                                      | 56         |
| 2.5.4    | Initial Synchronization Process . . . . .                         | 58         |
| 2.6      | Summary . . . . .                                                 | 59         |
| <b>3</b> | <b>Systematic Analysis of Non-Financial Blockchain Content</b>    | <b>61</b>  |
| 3.1      | Motivation . . . . .                                              | 61         |
| 3.1.1    | Contributions . . . . .                                           | 62         |
| 3.2      | Problem Analysis . . . . .                                        | 64         |
| 3.2.1    | History of Bitcoin Content Insertion . . . . .                    | 64         |
| 3.2.2    | Model for Blockchain Content Insertion and Distribution . . . . . | 66         |
| 3.3      | Analysis of Content Insertion Methods . . . . .                   | 67         |
| 3.3.1    | Low-Level Content Insertion Methods . . . . .                     | 68         |
| 3.3.2    | Content Insertion Services . . . . .                              | 72         |
| 3.4      | Benefits and Risks of Blockchain Content . . . . .                | 74         |
| 3.4.1    | Benefits of Blockchain Content Insertion . . . . .                | 74         |
| 3.4.2    | Negative Consequences of Blockchain Content Insertion . . . . .   | 75         |
| 3.5      | Analysis of Non-Financial Content . . . . .                       | 81         |
| 3.5.1    | Measurement Framework and Methodology . . . . .                   | 81         |
| 3.5.2    | Quantitative Analysis of Content Insertion . . . . .              | 86         |
| 3.5.3    | Assessment of Blockchain Files . . . . .                          | 95         |
| 3.6      | Related Work . . . . .                                            | 99         |
| 3.7      | Conclusion and Future Work . . . . .                              | 101        |
| <b>4</b> | <b>Mitigation of Unwanted Blockchain Content</b>                  | <b>103</b> |
| 4.1      | Motivation . . . . .                                              | 103        |
| 4.1.1    | Constraints for Mitigation Schemes . . . . .                      | 105        |
| 4.1.2    | Contributions . . . . .                                           | 107        |
| 4.2      | Prevention Strategies Against Unwanted Content . . . . .          | 107        |

|          |                                                                    |            |
|----------|--------------------------------------------------------------------|------------|
| 4.2.1    | Related Work . . . . .                                             | 109        |
| 4.2.2    | Problem Statement . . . . .                                        | 110        |
| 4.2.3    | Filtering Content-Holding Transactions . . . . .                   | 112        |
| 4.2.4    | Mandatory Minimum Transaction Fees . . . . .                       | 114        |
| 4.2.5    | Hardened On-Chain Addresses . . . . .                              | 120        |
| 4.2.6    | Summary and Future Work . . . . .                                  | 124        |
| 4.3      | Moderation of Blockchain Content . . . . .                         | 125        |
| 4.3.1    | Related Work . . . . .                                             | 126        |
| 4.3.2    | Missing Swift and Transparent Redactions . . . . .                 | 129        |
| 4.3.3    | Cryptographic Building Blocks . . . . .                            | 131        |
| 4.3.4    | RedactChain Overview . . . . .                                     | 135        |
| 4.3.5    | Detecting Unwanted Blockchain Content . . . . .                    | 137        |
| 4.3.6    | Decentralized Redaction Process . . . . .                          | 139        |
| 4.3.7    | Coordinating Short-Lived Redaction Juries . . . . .                | 142        |
| 4.3.8    | Evaluation . . . . .                                               | 145        |
| 4.3.9    | Summary and Future Work . . . . .                                  | 150        |
| 4.4      | Conclusion . . . . .                                               | 152        |
| <b>5</b> | <b>Retrofitting Blockchains with Pruning Capabilities</b>          | <b>153</b> |
| 5.1      | Motivation . . . . .                                               | 154        |
| 5.1.1    | Problem Analysis . . . . .                                         | 155        |
| 5.1.2    | Contributions . . . . .                                            | 158        |
| 5.2      | Survey of Related Work . . . . .                                   | 159        |
| 5.2.1    | Survey Criteria . . . . .                                          | 159        |
| 5.2.2    | Retrospective Changes to Established Blockchain Systems . . . . .  | 159        |
| 5.2.3    | Alternative Blockchain Designs with Pruning Capabilities . . . . . | 162        |
| 5.3      | Design Goals . . . . .                                             | 164        |
| 5.4      | CoinPrune Overview . . . . .                                       | 165        |
| 5.5      | Retrofittable Block Pruning . . . . .                              | 167        |
| 5.5.1    | Data Management . . . . .                                          | 167        |
| 5.5.2    | Coordination of Established Nodes . . . . .                        | 169        |
| 5.5.3    | Bootstrapping of New Nodes . . . . .                               | 169        |

|          |                                                             |            |
|----------|-------------------------------------------------------------|------------|
| 5.6      | Handling Application-Level Data . . . . .                   | 170        |
| 5.6.1    | Obfuscation of Illicit Data from the UTXO Set . . . . .     | 170        |
| 5.6.2    | Preservation of Application-Level Data . . . . .            | 173        |
| 5.7      | Seamless Integration into Bitcoin . . . . .                 | 174        |
| 5.7.1    | Additional On-Chain Data . . . . .                          | 174        |
| 5.7.2    | Adaptions to the Peer-to-Peer Protocol . . . . .            | 174        |
| 5.8      | Security Discussion . . . . .                               | 175        |
| 5.8.1    | Snapshot Validity . . . . .                                 | 175        |
| 5.8.2    | Reliability of Reaffirmations . . . . .                     | 177        |
| 5.8.3    | Peer-to-Peer Attacks . . . . .                              | 178        |
| 5.9      | Performance Evaluation . . . . .                            | 179        |
| 5.9.1    | Testbed Setup for Synchronization Measurements . . . . .    | 179        |
| 5.9.2    | Storage Savings . . . . .                                   | 179        |
| 5.9.3    | Evaluation of Synchronization Performance . . . . .         | 181        |
| 5.10     | Conclusion and Future Work . . . . .                        | 183        |
| <b>6</b> | <b>Blockchain-based Bootstrapping of Anonymity Services</b> | <b>185</b> |
| 6.1      | Motivation . . . . .                                        | 186        |
| 6.1.1    | Problem Analysis . . . . .                                  | 186        |
| 6.1.2    | Contributions . . . . .                                     | 190        |
| 6.2      | Design Goals . . . . .                                      | 191        |
| 6.3      | AnonBoot Overview . . . . .                                 | 192        |
| 6.3.1    | Design Intuition . . . . .                                  | 192        |
| 6.3.2    | Overview of Bootstrapping Steps . . . . .                   | 193        |
| 6.4      | Sybil-Resistant Index of Peers and Services . . . . .       | 195        |
| 6.4.1    | Message Types . . . . .                                     | 195        |
| 6.4.2    | Pulse-based Message Release . . . . .                       | 198        |
| 6.5      | Bootstrapping Secure Anonymity Services . . . . .           | 199        |
| 6.5.1    | Connecting Users and Privacy Peers . . . . .                | 200        |
| 6.5.2    | Local Selection of Privacy Peers . . . . .                  | 200        |
| 6.5.3    | Service Requests for Peer Election . . . . .                | 201        |
| 6.6      | Realization of Use Cases . . . . .                          | 202        |

|          |                                                              |            |
|----------|--------------------------------------------------------------|------------|
| 6.6.1    | Decentralized Onion Routing via AnonBoot . . . . .           | 202        |
| 6.6.2    | Shuffling Networks and Cryptocurrency Tumblers . . . . .     | 203        |
| 6.6.3    | User-Centered Redaction Juries . . . . .                     | 204        |
| 6.7      | Security Discussion . . . . .                                | 205        |
| 6.7.1    | Proof of Work Against Sybil Attacks . . . . .                | 206        |
| 6.7.2    | Security of Bootstrapped Services . . . . .                  | 207        |
| 6.8      | Performance Evaluation . . . . .                             | 210        |
| 6.8.1    | Synchronization with Host Blockchain . . . . .               | 210        |
| 6.8.2    | Small Blockchain Footprint and Low Costs . . . . .           | 211        |
| 6.9      | Related Work . . . . .                                       | 212        |
| 6.10     | Conclusion and Future Work . . . . .                         | 213        |
| <b>7</b> | <b>Conclusion</b>                                            | <b>215</b> |
| 7.1      | Contributions . . . . .                                      | 216        |
| 7.1.1    | Systematic Analysis of Non-Financial Blockchain Content . .  | 216        |
| 7.1.2    | Mitigation of Unwanted Blockchain Content . . . . .          | 216        |
| 7.1.3    | Retrofitting Blockchains with Pruning Capabilities . . . . . | 217        |
| 7.1.4    | Blockchain-based Bootstrapping of Anonymity Services . . . . | 218        |
| 7.2      | Future Work . . . . .                                        | 219        |
| 7.3      | Closing Remarks . . . . .                                    | 220        |
|          | <b>Abbreviations and Acronyms</b>                            | <b>221</b> |
|          | <b>Bibliography</b>                                          | <b>223</b> |