

Contents

Abstract	iii
Kurzfassung	v
Contents	vii
List of Abbreviations	xi
1 An Introduction to Critical Infrastructure Communications	1
1.1 Motivation	1
1.2 Research Challenges, Methodology and Thesis Structure	5
1.3 Overview of Key Contributions	8
2 Applications and Communication Requirements of Critical Infrastructures	11
2.1 Smart Power Transmission and Distribution Grids	11
2.1.1 Use Cases and Requirements of Distributed Energy Infrastructures	12
2.1.2 Relevant Technologies and Protocols	13
2.2 5G Communication Infrastructures	16
2.2.1 5G Communications - Use Cases and Requirements	16
2.2.2 Relevant Concepts and Technologies	19
3 Software-Defined Networking based Critical Infrastructure Communications: Building Blocks and Performance Evaluation	23
3.1 Traditional Approaches to Critical Communication Infrastructures	23
3.2 Software-Defined Networking driven Communication Systems	25
3.2.1 The Southbound Interface: Connecting Data and Control Plane	27
3.2.2 East- and Westbound Interfaces: Enabling Multi-Controller Interaction	29
3.2.3 The Northbound Interface: Exposing Network Control to Applications	30
3.2.4 The SUCCESS Software-Defined Networking Controller Framework	30
3.3 Network Function Virtualization	31

3.4	Approaches Employed for Performance Evaluation	33
3.4.1	Simulation-based Studies	33
3.4.2	Empirical Validation Approaches	37
4	Robust and Fault-Tolerant Hardened Critical Infrastructure Communications	41
4.1	Objectives for Hardening Smart Grid Communication Networks . .	41
4.2	Overview of Related Works	42
4.2.1	State of the Art in Data Plane Recovery	43
4.2.2	Contemporary Strategies for Control Plane Resilience	44
4.3	Solution Approaches to SDN-enabled Data Plane Resilience	46
4.3.1	Methodology and Reference Scenario	49
4.3.2	Evaluation Scenario: Mitigating Intra-Smart-Substation Communication Link Failures	51
4.3.3	Summary and Classification in Relation to the State of the Art	57
4.4	Proposed Control Plane Resilience Strategies	58
4.4.1	Evaluation Methodology and Reference Scenario	62
4.4.2	Approach A: Primary/Secondary Controller Failover	63
4.4.3	Approach B: A Novel, Broker-based Approach to Control Plane Resilience	66
4.4.4	Summary and Comparison to Existing Control Plane Recovery Mechanisms	68
4.5	Conclusion	70
5	Evaluation of Flexible Softwarized Communications for Sliced Critical Infrastructures	71
5.1	Motivation and Goals for Network Softwarization in Critical Communications	72
5.2	Survey of Related Works on Network Softwarization	73
5.2.1	Bare Metal and fully Virtualized Data Plane Paradigms . . .	73
5.2.2	Network Slicing in Wireline Networks	74
5.3	Empirical Comparison of Bare Metal and Fully Virtualized Data Plane Solutions	75
5.3.1	Evaluation Strategy and Reference Scenarios	77
5.3.2	Scenario A: Packet Forwarding Performance in Virtualized Infrastructures	80
5.3.3	Scenario B: Fast-Failover on Virtualized Data Planes	83
5.3.4	Summary of Results and Insights achieved	85
5.4	Proposed Solution for SDN and NFV-driven 5G Core Network Slicing	86
5.4.1	Evaluation Strategy and Reference Scenarios	88
5.4.2	Tiered Study of Key Performance Indicators	94
5.4.3	Conclusion	102
5.5	Summary of gained Insights	103

6 Analysis of Scalable, Software-Defined Networking driven Critical Infrastructure Communications	105
6.1 Drivers for enabling Large-Scale Critical Infrastructure Communications	106
6.2 Related Work on Large-Scale Software-Defined Networking driven Critical Infrastructures	106
6.2.1 Simulation-based Studies	106
6.2.2 Edge Cloud enabled Communications	107
6.3 Simulation-based Evaluation of SDN-driven Large-Scale Smart Grids	109
6.3.1 Evaluation Strategy and Reference Scenario	109
6.3.2 Scenario-based Assessment: SDN-driven Large-Scale Smart Distribution Grid Deployment	114
6.3.3 Conclusion	115
6.4 Edge Cloud enabled Communication Services for Critical Infrastructures	116
6.4.1 Use Case: Edge Clouds for Intelligent Transportation Services - Smart Intersections . .	121
6.4.2 Overview of Key Results	130
6.5 Conclusion and Summary of Main Contributions	131
7 Conclusion and Future Work	133
7.1 Closing Summary	133
7.2 Outlook on Future Research Directions	135
7.2.1 Fully Virtualized Self-Organizing Sliced Communication Infrastructures . . .	135
7.2.2 Software-Defined Networking Orchestrated Time-Sensitive Industrial Networks	135
7.2.3 Edge Cloud based 5G Radio Access Networks for Cellular Power Grids	136
Bibliography	139
Scientific Activity Report	157