

# Design and Performance Evaluation of Adaptive Critical Infrastructure Communications based on Software-Defined Networking

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**Design and Performance Evaluation of  
Adaptive Critical Infrastructure Communications  
based on Software-Defined Networking**

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# Abstract

Modern societies increasingly depend on critical infrastructures such as transportation, Information and Communication Technology (ICT) as well as energy systems. The latter constitutes a particularly demanding application and, in an effort to reduce its impact on the environment while boosting efficiencies, is undergoing a paradigm shift towards renewable, distributed generation of electricity. This transformation towards Smart Grids in turn requires an unprecedented degree of monitoring and control on all levels of the electrical system. Accordingly, pervasive ICT infrastructures, capable of meeting stringent requirements in terms of robustness, flexibility, and performance, are needed.

This work aims at meeting these challenges by applying the concepts of Software-Defined Networking (SDN) and Network Function Virtualization (NFV) to critical infrastructure communications. Both approaches represent a paradigm shift away from integrated, fixed-function devices towards flexibly programmable, i.e. softwarization- and virtualization-driven, ICT infrastructures. These 5G core network technologies are evaluated via simulations and empirical studies, focusing on their suitability for use in future Smart Grids. Key contributions to the state of the art in fault-tolerance, flexibility and scalability are introduced by way of novel strategies for resilience, core network slicing and scalable Edge Clouds, and integrated into a comprehensive SDN controller framework. The developed solutions are shown to fulfil the most demanding requirements of relevant critical infrastructure protocols and scenarios, derived from real-world deployments as well as research projects.



# Kurzfassung

Moderne Gesellschaften sind zunehmend von kritischen Infrastrukturen wie Verkehrsnetzen, Informations- und Kommunikationstechnologien (IKT) sowie Energiesystemen abhängig. Letztere stellen eine besonders anspruchsvolle Anwendung dar und vollziehen in dem Bestreben ihre Auswirkungen auf die Umwelt zu verringern und gleichzeitig die Effizienz zu steigern, einen Paradigmenwechsel hin zu einer erneuerbaren, dezentralen Stromerzeugung. Diese Transformation hin zu sogenannten Smart Grids erfordert wiederum ein noch nie dagewesenes Maß an Überwachung und Kontrolle auf allen Ebenen der elektrischen Energiesysteme. Dementsprechend werden allgegenwärtige IKT-Infrastrukturen benötigt, die in der Lage sind höchste Anforderungen in Bezug auf Robustheit, Flexibilität und Leistung zu erfüllen.

Ziel dieser Arbeit ist es, diesen Herausforderungen zu begegnen, indem die Konzepte des Software-Defined Networking (SDN) und der Network Function Virtualization (NFV) auf die Kommunikation kritischer Infrastrukturen angewendet werden. Beide Ansätze stellen einen Paradigmenwechsel weg von integrierten Geräten mit festen Funktionen hin zu flexibel programmierbaren, d.h. auf Software und Virtualisierung basierenden IKT-Infrastrukturen dar. Diese 5G-Kernnetztechnologien werden im Rahmen von Simulationen und empirischen Studien evaluiert, wobei der Schwerpunkt auf ihrer Eignung für den Einsatz in zukünftigen Smart Grids liegt. Schlüsselbeiträge zum Stand der Technik in Bezug auf Fehlertoleranz, Flexibilität und Skalierbarkeit werden durch neuartige Strategien für Ausfallsicherheit, Kernnetz-Slicing und skalierbare Edge-Clouds vorgestellt, die in ein umfassendes SDN-Controller-Framework integriert sind. Mit Hilfe von Simulationen und empirischen Analysen wird gezeigt, dass die entwickelten Lösungen die anspruchsvollsten Anforderungen der relevanten Protokolle und Szenarien für kritische Infrastrukturen erfüllen, welche aus Demonstrationsumgebungen und Forschungsprojekten abgeleitet wurden.





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# List of Abbreviations

<b>3GPP</b>	3rd Generation Partnership Project . . . . .	9
<b>5G</b>	5th Generation of Mobile Communications . . . . .	6
<b>5QI</b>	5G Quality of Service Identifier . . . . .	18
<b>AC</b>	Alternating Current . . . . .	78
<b>AF</b>	Application Function . . . . .	20
<b>AI</b>	Artificial Intelligence . . . . .	125
<b>AMF</b>	Access and Mobility Management Function . . . . .	20
<b>API</b>	Application Programming Interface . . . . .	27
<b>AR</b>	Augmented Reality . . . . .	16
<b>ASIC</b>	Application Specific Integrated Circuit . . . . .	39
<b>AUSF</b>	Authentication Server Function . . . . .	20
<b>BBU</b>	Baseband Unit . . . . .	136
<b>BFD</b>	Bidirectional Forwarding Detection . . . . .	43
<b>BGP</b>	Border Gateway Protocol . . . . .	76
<b>CARP</b>	Common Address Redundancy Protocol . . . . .	44
<b>CDF</b>	Cumulative Distribution Function . . . . .	128
<b>CEN</b>	Comité Européen de Normalisation . . . . .	11
<b>CENELEC</b>	Comité Européen de Normalisation Électrotechnique . . . . .	11
<b>CI</b>	Critical Infrastructure . . . . .	6
<b>CNI</b>	Communications Networks Institute . . . . .	48
<b>COTS</b>	Commercial Off-The-Shelf . . . . .	25
<b>CP</b>	Control Plane . . . . .	19
<b>CPS</b>	Cyber-Physical System . . . . .	72
<b>CPU</b>	Central Processing Unit . . . . .	39
<b>CRC</b>	Cyclic Redundancy Check . . . . .	83
<b>CUPS</b>	Control and User Plane Separation . . . . .	19
<b>DDoS</b>	Distributed Denial of Service . . . . .	90
<b>DER</b>	Distributed Energy Resource . . . . .	3
<b>DES</b>	Discrete-Event Simulation . . . . .	34
<b>DMS</b>	Distribution Grid Management System . . . . .	12
<b>DMZ</b>	Demilitarized Zone . . . . .	13
<b>DN</b>	Data Network . . . . .	20
<b>DP</b>	Data Plane . . . . .	25
<b>DSCP</b>	Differentiated Service Code Point . . . . .	24
<b>DSO</b>	Distribution System Operator . . . . .	6
<b>EC</b>	Edge Cloud . . . . .	20

## Contents

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<b>eMBB</b>	enhanced Mobile Broadband . . . . .	16
<b>EMI</b>	Electromagnetic Interference . . . . .	14
<b>EPC</b>	Evolved Packet Core . . . . .	136
<b>ETSI</b>	European Telecommunications Standards Institute . . . . .	9
<b>EV</b>	Electric Vehicle . . . . .	4
<b>FBOSS</b>	Facebook Open Switching System . . . . .	76
<b>FCD</b>	Floating Car Data . . . . .	17
<b>FCS</b>	Frame Check Sequence . . . . .	83
<b>FFG</b>	Fast-Failover Group . . . . .	28
<b>FLP</b>	Fast Link Pulse . . . . .	52
<b>FRR</b>	Fast Reroute . . . . .	58
<b>FSM</b>	Finite-State Machine . . . . .	35
<b>FTP</b>	File Transfer Protocol . . . . .	90
<b>gNodeB</b>	next generation Node B . . . . .	117
<b>GBR</b>	Guaranteed Bit Rate . . . . .	18
<b>GOOSE</b>	Generic Object Oriented Substation Events . . . . .	15
<b>GPS</b>	Global Positioning System . . . . .	37
<b>GUI</b>	Graphic User Interface . . . . .	13
<b>HB</b>	Heartbeat . . . . .	47
<b>HMI</b>	Human Machine Interface . . . . .	50
<b>HTB</b>	Hierarchical Token Bucket . . . . .	96
<b>HTTP</b>	Hypertext Transfer Protocol . . . . .	90
<b>HV</b>	High Voltage . . . . .	2
<b>ICMP</b>	Internet Control Message Protocol . . . . .	110
<b>ICE</b>	Interface Corruption Equipment . . . . .	40
<b>ICT</b>	Information and Communication Technology . . . . .	2
<b>IDS</b>	Intrusion Detection System . . . . .	13
<b>IEC</b>	International Electrotechnical Commission . . . . .	13
<b>IED</b>	Intelligent Electronic Device . . . . .	14
<b>IEEE</b>	Institute of Electrical and Electronic Engineers . . . . .	37
<b>IoT</b>	Internet of Things . . . . .	16
<b>IP</b>	Internet Protocol . . . . .	13
<b>IPMI</b>	Intelligent Platform Management Interface . . . . .	37
<b>ISG</b>	Industry Specification Group . . . . .	118
<b>ISO</b>	International Standardisation Organisation . . . . .	28
<b>ISO/OSI</b>	International Standardisation Organisation / Open Systems Interconnect . . . . .	28
<b>ISP</b>	Internet Service Provider . . . . .	21
<b>IT</b>	Information Technology . . . . .	1
<b>ITS</b>	Intelligent Transportation System . . . . .	6
<b>ITT</b>	Inter-Transmission Time . . . . .	15
<b>KPI</b>	Key Performance Indicator . . . . .	4
<b>LDAP</b>	Lightweight Directory Access Protocol . . . . .	13

<b>LSP</b>	Label Switched Path . . . . .	24
<b>LSR</b>	Label Switched Router . . . . .	24
<b>LTE</b>	Long Term Evolution . . . . .	75
<b>LV</b>	Low Voltage . . . . .	11
<b>MAC</b>	Media Access Control . . . . .	63
<b>MANO</b>	Management and Orchestration . . . . .	21
<b>MEC</b>	Mobile Edge Cloud / Mobile Edge Computing . . . . .	118
<b>MMS</b>	Manufacturing Message Specification . . . . .	16
<b>mMTC</b>	massive Machine Type Communication . . . . .	16
<b>MPLS</b>	Multiprotocol Label Switching . . . . .	24
<b>MTU</b>	Maximum Transmission Unit . . . . .	15
<b>MU</b>	Merging Unit . . . . .	50
<b>MV</b>	Medium Voltage . . . . .	11
<b>NAT</b>	Network Address Translation . . . . .	28
<b>NBI</b>	Northbound Interface . . . . .	30
<b>NC</b>	Network Calculus . . . . .	56
<b>NEF</b>	Network Exposure Function . . . . .	20
<b>NFV</b>	Network Function Virtualization . . . . .	6
<b>NGC</b>	Next Generation Core . . . . .	136
<b>NIC</b>	Network Interface Card . . . . .	83
<b>NOS</b>	Network Operating System . . . . .	33
<b>NR</b>	New Radio . . . . .	16
<b>NRF</b>	Network Repository Function . . . . .	20
<b>NSA</b>	Non-Standalone . . . . .	22
<b>NSSF</b>	Network Slice Selection Function . . . . .	20
<b>NTP</b>	Network Time Protocol . . . . .	13
<b>ODM</b>	Original Design Manufacturer . . . . .	76
<b>OF</b>	OpenFlow . . . . .	27
<b>ONF</b>	Open Networking Foundation . . . . .	27
<b>ONIE</b>	Open Network Install Environment . . . . .	33
<b>OS</b>	Operating System . . . . .	39
<b>OSPF</b>	Open Shortest Path First . . . . .	57
<b>OVS</b>	Open vSwitch . . . . .	32
<b>OXM</b>	OpenFlow Extensible Match . . . . .	28
<b>P4</b>	Programming Protocol-Independent Packet Processors . . . . .	76
<b>PCF</b>	Policy Control Function . . . . .	20
<b>PN</b>	Physical Network . . . . .	20
<b>pps</b>	packets per second . . . . .	40
<b>PPS</b>	Pulse Per Second . . . . .	51
<b>PRP</b>	Parallel Redundancy Protocol . . . . .	43
<b>PTP</b>	Precision Time Protocol . . . . .	37
<b>PV</b>	Photovoltaic . . . . .	3
<b>QoS</b>	Quality of Service . . . . .	13



## Contents

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<b>RAM</b>	Random Access Memory . . . . .	39
<b>RAN</b>	Radio Access Network . . . . .	20
<b>RAS</b>	Remote Access Service . . . . .	13
<b>REST</b>	Representational State Transfer . . . . .	30
<b>RRH</b>	Remote Radio Head . . . . .	136
<b>RSU</b>	Roadside Unit . . . . .	125
<b>RSVP</b>	Resource Reservation Protocol . . . . .	24
<b>RTU</b>	Remote Terminal Unit . . . . .	13
<b>SA</b>	Standalone . . . . .	22
<b>SAI</b>	Switch Abstraction Interface . . . . .	76
<b>SCADA</b>	Supervisory Control and Data Acquisition . . . . .	4
<b>SDN</b>	Software-Defined Networking . . . . .	6
<b>SDR</b>	Software-Defined Radio . . . . .	135
<b>SFP+</b>	Enhanced Small Form-Factor Pluggable . . . . .	39
<b>SG</b>	Smart Grid . . . . .	13
<b>SGAM</b>	Smart Grid Architecture Model . . . . .	11
<b>SIEM</b>	Security Information and Event Management . . . . .	13
<b>SLA</b>	Service Level Agreement . . . . .	21
<b>SMF</b>	Session Management Function . . . . .	20
<b>SON</b>	Self-Organizing Network . . . . .	135
<b>SONiC</b>	Software for Open Networking in the Cloud . . . . .	76
<b>SSH</b>	Secure Shell . . . . .	37
<b>SUCCESS</b>	Software-defined Universal Controller for Communications in Essential SystemS . . . . .	23
<b>SV</b>	Sampled Value . . . . .	15
<b>TASE.2</b>	Telecontrol Application Service Element 2 . . . . .	13
<b>TCAM</b>	Ternary Content-Addressable Memory . . . . .	76
<b>TCP</b>	Transmission Control Protocol . . . . .	16
<b>TDD</b>	Time-Division Duplex . . . . .	135
<b>TDMA</b>	Time-Division Multiple Access . . . . .	136
<b>TLS</b>	Transport Layer Security . . . . .	62
<b>ToS</b>	Type of Service . . . . .	24
<b>TSN</b>	Time-Sensitive Networking . . . . .	136
<b>TSO</b>	Transmission System Operator . . . . .	11
<b>UDM</b>	Unified Data Management . . . . .	20
<b>UDP</b>	User Datagram Protocol . . . . .	27
<b>UE</b>	User Equipment . . . . .	22
<b>UHD</b>	Ultra High Definition . . . . .	16
<b>UPF</b>	User Plane Function . . . . .	20
<b>URLLC</b>	Ultra-Reliable Low Latency Communication . . . . .	17
<b>vSwitch</b>	Virtualized Switch . . . . .	39
<b>V2X</b>	Vehicle-to-everything . . . . .	16
<b>VLAN</b>	Virtual Local Area Network . . . . .	27

<b>VM</b>	Virtual Machine . . . . .	32
<b>VNF</b>	Virtual Network Function . . . . .	31
<b>VPN</b>	Virtual Private Network . . . . .	32
<b>VR</b>	Virtual Reality . . . . .	16
<b>VRRP</b>	Virtual Router Redundancy Protocol . . . . .	44
<b>WAMPAC</b>	Wide Area Monitoring Protection and Control . . . . .	14
<b>WAN</b>	Wide Area Network . . . . .	13