# Enabling Hard Service Guarantees in Software-Defined Smart Grid Infrastructures

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#### Abstract

Information and Communication Technology (ICT) infrastructures play a key role in the evolution from traditional power systems to Smart Grids. Increasingly fluctuating power flows, sparked by the transition towards sustainable energy generation, become a major issue for power grid stability. To deal with this challenge, future Smart Grids require precise monitoring and control, which in turn demand for reliable, real-time capable and cost-efficient communications. For this purpose, we propose applying Software-Defined Networking (SDN) to handle the manifold requirements of Smart Grid communications. To achieve reliability, our approach encompasses fast recovery after failures in the communication network and dynamic service-aware network (re-)configuration. Network Calculus (NC) logic is embedded into our SDN controller for meeting latency requirements imposed by the standard IEC 61850 of the International Electrotechnical Commission (IEC). Thus, routing provides delay-optimal paths under consideration of existing cross traffic. Also, continuous latency bound compliance is ensured by combining NC delay supervision with means of flexible reconfiguration. For evaluation we consider the well-known Nordic 32 test system, on which we map a corresponding communication network in both experiment and emulation. The described functionalities are validated, employing

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realistic IEC 61850 transmissions and distributed control traffic. Our results show that hard service guarantees can be ensured with the help of the proposed SDN solution. On this basis, we derive extremely time critical services, which must not be subjected to flexible reconfiguration.

Keywords: Smart Grid Communications, Mission Critical Systems, Hard Service Guarantees, Software-Defined Networking, Network Calculus.

#### 1. Introduction

Future power systems are faced with severe challenges, caused by the transition from conventional to distributed, renewable generation [1]. To fully exploit the advantages and mitigate the drawbacks of fluctuating power generation from these energy resources, concepts such as Demand Side Management (DSM) and controllable loads/storages, e.g. scheduling Electric Vehicle (EV) charging, need to be applied. At the same time, the energy system has to deal with further volatile power transmissions, caused by increasing energy trade due to the liberalization of energy markets. Resulting from these challenges, precise monitoring and control of the system are indispensable for maintaining grid stability and avoiding cascading outages. Subsequently, appropriate Information and Communication Technology (ICT) infrastructures are required to ensure reliable, timely transfer of measurement data and control commands, in particular on transmission grid level [2, 3]. Quantitative requirements are given in the International Electrotechnical Commission (IEC)'s standard IEC 61850, which is set to become the prevailing normative for power grid communications. It defines intervals as low as 250  $\mu$ s and maximum allowed latencies of 5 ms for measurement data transmission and protection tripping respectively [4]. Meanwhile, distribution grid communications deal with numerous protocols and a variety of different access technologies [5]. Overall, an increasing number of Intelligent Electronic Device (IED), each with distinct service requirements, will be connected to wide area communication networks.

To cope with these specific demands of Smart Grid communications, we pro-

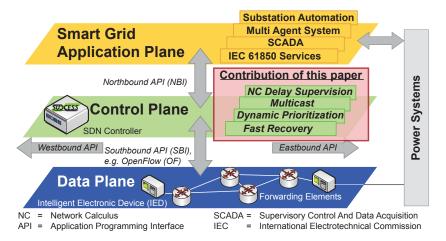


Figure 1: Solution approaches addressed in this paper, mapped on the Software-Defined Networking for Smart Grids concept, introduced in [9]

pose a comprehensive framework, building on the concept of Software-Defined Networking (SDN). In this way, we are able to provide hard service guarantees with traffic flow granularity. SDN constitutes a promising new take on networking, offering flexible, dynamic configuration of communication infrastructures [6]. Following the paradigm of separating data and control planes, SDN establishes a programmable controller platform. It enables managing traffic flows, profiting from a global network view. There exist various mechanisms for enhancing particular aspects of communications' Quality-of-Service (QoS). Yet, they typically suffer from vendor specific peculiarities, poor integration and overly complicated configuration [7]. In contrast, our approach is able to address the multitude of diverging requirements, while allowing for straightforward extension and configuration. In particular, this concept provides means for fast failure recovery, dynamic prioritization and queue configuration under the overall paradigm of application- and QoS-awareness. Network Calculus (NC) algorithms [8] are incorporated into our SDN controller to predict and monitor end-to-end delays of traffic flows analytically. Hence, violations of delay bounds can be identified in time to activate counter-measures, ensuring continuous fulfillment of hard real-time guarantees.

The main contributions of this paper are the following:

- Software-Defined Networking enabled service-centric network configuration and adaption for Smart Grids, providing hard service guarantees
- the integration of NC into SDN-driven network control for delay supervision and routing to ensure real-time capable communications at all times

Figure 1 provides an overview of our concept for SDN-enabled Smart Grid communications, highlighting interactions between ICT and power system applications. We evaluate our concepts, considering IEC 61850 communications as well as a Multi-Agent System (MAS) for distributed control on a fiber-based communication infrastructure for the Nordic 32 test system [10]. Both empirical measurements and emulations of the whole infrastructure are utilized. In addition, the proposed concepts may be adapted to other mission critical systems such as transportation or rescue services.

This work has been carried out as part of larger scale research efforts, i.e. DFG research unit 1511 and the Franco-German project BERCOM. Subsequently, Smart Grid requirements were synchronized and solution approaches discussed with power system experts and utilities such as EDF.

The remainder of this work is structured as follows: Section 2 provides an overview of the state-of-the-art, detailing the requirements of Smart Grid communications and introducing the main principles of SDN and NC. The section is completed by an overview of related work. Next, we describe our solution approach based on the SDN controller framework (Section 3). In Sections 4 and 5 a description of the Smart Grid scenario and an overview of the developed testbed set-up are provided. Afterwards, empirical, emulation and analytical evaluation results are presented in Section 6. Finally, the paper concludes with a summary and an outlook on future work (Section 7).

# 2. State-of-the-Art on Smart Grid Communications, Software-Defined Networking and Associated Performance Evaluation

This section reviews Smart Grid communication requirements and reflects on the state-of-the-art of Software-Defined Networking (SDN) and Network Calculus, for enabling respectively verifying hard service guarantee compliance. Afterwards, results of related work are described and compared to this article.

#### 2.1. Smart Grid Communication Use Cases

Smart Grid communication requirements can be roughly divided into distribution and transmission grid use cases, as detailed below. While these power system levels exhibit widely diverging demands, SDN offers an integrated approach for associated communications.

#### 2.1.1. Managing the Distribution Power Grid

Communication-dependent applications in the distribution power grid comprise Automated Meter Reading (AMR), DSM, monitoring and control of Distributed Energy Resources (DER), as well as coordination of EV charging. AMR is considered a fundamental function of smart distribution grids, providing measurement data as the basis for more advanced applications, such as novelty detection power meters [11]. For this concept machine learning is deployed on distributed energy measurement data to optimize the energy consumption times of end users. Also, anomalies can be detected, revealing energy consumption that deviates from common patterns (e.g. non-technical losses). This concept can be further enhanced by integrating an intelligent decision-making system for reducing energy consumption on basis of temporal correlations [12]. High precision decision-making is achieved with the help of artificial neural networks. Such approaches mark the transition to artificially intelligent (AI) energy systems, focused on energy efficiency, providing an evolution of DSM.

Design and operation of ICT infrastructures for the distribution power grid are driven by large numbers of devices, heterogeneity of protocols and technologies [13]. While IEC 61850 becomes increasingly important for DER control, dedicated sets of protocols are applied for AMR (e.g. IEC 62056, DLMS/COSEM) and EV charging (e.g. ISO 15118 and OCCP). For physical transmission, various wired (Power Line Communications (PLC), broadband cable) and wireless access technologies (WiFi, cellular) are considered. Moreover, driven by

business-to-consumer use cases, aspects like role management, authentication and billing play an important role.

#### 2.1.2. Controlling the Transmission Power Grid

In contrast to distribution systems, communications on the transmission grid level focus on requirements such as reliability, real-time capability and security. Use cases involve substation automation including extremely time critical protection functions, Wide-Area Monitoring Protection and Control (WAMPAC) and Supervisory Control and Data Acquisition (SCADA). Fiber-optic infrastructures are regarded as main transmission medium, whereas cellular networks are considered as alternative or back-up solution for the network access domain.

Table 1: Smart Grid timing requirements, specified in IEC 61850-5 [4]

Transfer Time Class	Maximum Transfer Time [ms]	Type of Transfer	
0	> 1000	files, events, logs	
1	1000	events, alarms	
2	500	operator commands	
3	100	slow automatic interactions	
4	20	fast automatic interactions	
5	10	releases, status changes	
6	3	trips, blockings	

Centralized Power System Control. SCADA provides the basis for centralized grid control functionalities. Protocol-wise IEC 60870 is currently still widely applied for this purpose. However, IEC 61850, originating from substation automation, is about to become the dominating protocol throughout transmission system communications (as well as for some distribution grid applications). It employs a holistic approach, covering detailed data models for devices and functions, abstract communication service descriptions as well as actual protocols. Measurement values are transmitted in fixed intervals of 250  $\mu$ s, us-

ing Sampled Value (SV) messaging. The Generic Object Oriented Substation Event (GOOSE) service is applied for exchanging statuses and issuing switching commands. Both message types are encapsulated into Ethernet packets directly. GOOSE operates semi-regularly with periodic status messages in intervals of e.g. 1s, whereas commands are issued in response to events and are repeated in increasing intervals starting at 1ms. Meanwhile, Manufacturing Message Specification (MMS) utilizes client-server-based TCP/IP communication for tasks like software updates, configuration and measurement reports. Table 1 provides an overview of end-to-end timing demands for different applications in IEC 61850, regardless of communication failures. The requirements are divided into corresponding Transmission Traffic Classes (TTC), defining maximum transfer times [4].

Distributed Power System Control. Differing from the common SCADA approach, power systems may also be controlled in a distributed manner, utilizing for example a Multi-Agent System (MAS). Such an MAS is introduced in [14], placing agents at substations of the power grid. These agents utilize local information along with data from adjacent substations, received via inter-agent communication, to gain an estimate of the surrounding power grid's state. In case emergency conditions are detected, the agents coordinate counter-measures and apply local assets to stabilize voltage and prevent black-outs. For example, set points of High Voltage Direct Current (HVDC)-converters and power flow controllers can be changed. Also, re-dispatch of flexible generation and load may be initiated. A first integration between a JAVA-based implementation of this distributed grid control and our SDN controller framework was achieved in [15].

#### 2.2. Software-Defined Networking Enabled Communication Systems

Software-Defined Networking is a novel approach towards networking, based on the idea of separating control and data plane [6]. Therefore, control functionalities are abstracted from networking nodes and consolidated at a dedicated instance, known as the SDN controller. Hence, data plane devices become SDN switches, handling physical transmission of packets only. Unknown traffic flows are forwarded to the SDN controller for classification. This central component handles routing and installs corresponding forwarding rules at all relevant devices throughout the network. Subsequent packets of the same traffic flow are handled by the data plane components on basis of the rules established previously. Communication between the SDN controller and the forwarding elements is handled via the so-called Southbound Interface (SBI) with Open Flow (OF) [16] being the most prominent – de-facto standard – protocol for this purpose [17].

One major benefit of SDN is the controller's programmability, which – in conjunction with its global network view – can be used to adapt dynamically to changes in the communication network. Moreover, it allows for straightforward integration of a variety of different approaches and algorithms, like for example traffic engineering capabilities of Multi Protocol Label Switching (MPLS). While integrating such functionalities, SDN obviates overly complex configuration, usually associated with such approaches [7]. Thus, network management and control are simplified significantly. Through its Northbound Interface (NBI) the SDN controller discloses means of conveying communication requirements and influencing network behavior to external applications. Contrary to the SBI, there is no common protocol for the NBI, though the Representational State Transfer (REST) Application Programming Interface (API) is in widespread use [18]. To achieve scalability of the SDN approach, i.e. for controlling large infrastructures, interaction with other controllers and legacy networks is enabled via the westbound and eastbound interface respectively.

Today, SDN is already widely deployed in data centers of companies such as Alphabet/Google [19] and is considered as the foundation for communications in the core of 5G mobile communication networks [20].

# 2.3. Network Calculus for the Performance Evaluation of Communication Infrastructures

To obtain a precise, real-time view on the delay of Smart Grid communications, NC is integrated into the controller framework as an analytical modeling approach for delay computation. NC, originating from the initial works of Cruz [21] in the early 1990s, is a well-established method for the worst-case analysis of communication networks. It is suited for arbitrary types of traffic as the approach is agnostic to statistical distribution functions, providing performance bounds only. Current advancements of NC favor the use of tighter, stochastic bounds, which come at the price of small violation probabilities [22]. In this work, however, the original, deterministic NC is applied, as timing requirements of communications in transmission power grids are extremely strict and violations may result in a fatal collapse of the system. Hence, thorough, deterministic delay bounds, excluding any violations, are considered most suitable.

Originating from NC terminology, we introduce *flow-of-interest* and *cross* traffic flows as major terms for describing network behavior in this article.

- Flow-of-interest refers to the packet transfer, which is in the current focus of analysis.
- Cross traffic flows are other transmissions that are concurrently active on the same network and may interfere with the flow-of-interest.

To model traffic, arriving to the communication system, we employ the frequently used, leaky (token) bucket arrival curve in Equation 1.

$$\alpha(t) = \sigma + \rho \cdot t,\tag{1}$$

where  $\sigma$  is the maximum packet size and  $\rho$  the sustained date rate requirement of the traffic flow. These parameters follow pre-defined values per assigned traffic/priority class. To map the service, which is offered to the traffic flow by network elements such as links or switches, the concept of service curves is adopted. Here, we use rate latency curves per outgoing switch port, considering

data rate R and propagation delay  $T_{pr}$  of the link as well as transmission  $(T_{tr})$  and switching delay  $(T_{sw})$ :

$$\beta(t) = R \cdot [t - T]^+, \tag{2}$$

with  $T = T_{pr} + T_{tr} + T_{sw}$ . By linking arrival and service curves, the delay and backlog, that is experienced by the flow-of-interest at the respective network element, can be determined. To obtain the traffic flow's overall network delay bound directly, NC utilizes the concept of the end-to-end service curve. It is calculated as the convolution of all service curves on the flow's path, as given by Equation 3.

$$\beta_{end-to-end,i}(t) = \beta_{1,i}(t) \otimes ... \otimes \beta_{n,i}(t), \tag{3}$$

with 1...n being the index of the switches on the path between source and destination. The interference of other transmissions, cross-traffic flows, is captured by the left-over-service curve  $\beta_{k,i}(t)$  with i being the index of the flow-of-interest and k identifying the respective switch. It is defined by Equation 4 and describes the service, which can still be provided to the flow-of-interest after taking into account interfering traffic.

$$\beta_{k,i}(t) = \beta_{k,base_i}(t) - \sum_{j=i}^{m} (\alpha_{k,j}(t - \Theta)), \qquad (4)$$

where cross traffic flows of same or higher priority (j = i...m) reduce the service available to flow i. Subsequently, the cross traffic arrival curves  $\alpha_{k,j}$  of flow j at node k are subtracted from the specific base service curve of flow i. For flows of higher priority (j > i) strict prioritization is assumed, resulting in  $\Theta = 0$ , whereas for flows of the same priority First In First Out (FIFO) scheduling applies, introducing  $\Theta$  as additional level of flexibility.

## 2.4. Related Work

In recent years, SDN has been a major topic of research with numerous related publications. Hence, our review focuses on a subset of these works, i.e. papers which apply SDN in the context of Smart Grids or aim at integrating SDN with NC.

Starting with the latter, Guck et al. split online routing and NC-based resource allocation, achieving average link utilization close to the results of mixed-integer programming in software-defined industrial ICT infrastructures [23]. In contrast to our approach, performance is assessed individually for each node, instead of applying end-to-end bounds, which are known to be tighter [22]. NC is applied in [24] to create a high-level abstraction model of network service capabilities, guaranteeing inter-domain end-to-end QoS. Thus, the authors derive the required bandwidth of services, whereas this work focuses on end-toend latency guarantees. In [25] a variation of NC serves as basis for a multiconstraint flow scheduling algorithm in SDN-enabled Internet-of-Things (IoT) infrastructures. The performance of SDN deployments is evaluated, modeling SDN controller-switch interactions with NC in [26]. Yet, computations are performed offline as the approach is not coupled with an actual SDN set-up. Similarly, Huang et al. validate their proposed hybrid scheduling approach for SDN switches by applying offline NC analysis [27]. In [28] NC is employed for the analysis of SDN scalability. Therefore, the authors determine worst case delay bounds on the interaction between network nodes and SDN controller. The approach considers switch internals and utilizes similarities between flow tables and caches. Evaluations indicate sensitivity to parameters such as network and flow table size, traffic characteristics and delay, allowing to deduce recommendations for distributed controller concepts. Just as the previous two articles, publication [28] analyzes SDN-enabled infrastructures with the help of NC, but does not integrate it with the system.

In previous studies we modeled a traditional wide-area communication network for transmission systems on basis of IEC 61850 and evaluated its real-time capability using NC [29]. The developed framework serves as a starting point

for combining NC and SDN within this article.

A general overview of possible applications of SDN in Cyber-Physical Systems (CPSs) is given in [30]. With regard to Smart Grid communications, Cahn et al. proposed SDN-based configuration of a complete IEC 61850 substation environment [31]. Molina et al. propose an OF-enabled substation infrastructure, integrating IEC 61850 configuration into the Floodlight controller by reading Substation Configuration Description (SCD) files [32]. In this way, the approach is very similar to the concepts presented in [31]. Based on the configuration file, static traffic flows with different priorities are established. Mininet is employed to test functionalities such as traffic prioritization, detection of Denial-of-Service (DoS) attacks and load balancing. However, these use cases show only minor advancements compared to standard Floodlight, whereas the main contribution is automatic substation network configuration. In [33] SDN is utilized to design a network intrusion detection system for SCADA communications. To facilitate the communication between smart meters and the control centers, aggregation points are introduced to the SDN data plane in [34]. Planning of these is optimized with respect to minimal costs applying a mathematical model. In [35] SDN is used for establishing networked microgrids, enabling event-triggered communication. According to the authors, in this way costs are reduced, while system resilience is enhanced. The above publications illustrate specific use cases of SDN in Smart Grids and are included in this literature review mainly to illustrate the broad scope of possible applications.

Sydney et al. compare MPLS- and OF-based network control for power system communications, demonstrating that SDN achieves similar performance, while simplifying configuration [7]. The authors expanded their work by experiments on the GENI testbed [36]. Evaluations are performed using the example of demand response, where load shedding is triggered to maintain frequency stability. In this context, three functionalities are tested: fast failover, load balancing and QoS provisioning. Thus, the paper addresses topics quite similar to this article. However, no standard Smart Grid communication protocol is applied. Also, the publication is rather focused on the electrical side, whereas

some communication aspects are not studied in full detail. For example, the presented recovery process is comparably slow with delays of up to 2s and would require further optimization. In addition, our investigation considers further functionalities such as dynamic network reconfiguration and delay supervision. Mininet emulation, integrated with ns-3 simulation, is used in [37] to evaluate SDN-based failure recovery to wireless back-up links in a Smart Grid scenario. OF Fast Failover Group (FFG) are used in [38] to enable fault-tolerant multicast in Smart Grid ICT infrastructures. Both of the above papers tackle specific aspects of reliability in terms of fault-tolerance, which are not addressed in this work (utilization of wireless back-up paths and multicast recovery). Although, the discussed papers are limited to particular realizations of fault-tolerance concepts, they could provide valuable extensions of this work. In contrast, this work considers reliability in a broader sense, considering the fulfillment/enforcement of data rate and latency guarantees.

In previous work we proposed an SDN controller framework, which provides fault tolerance and dynamically adaptable service guarantees for Smart Grid communications [9, 15, 39]. Compared to these publications and other related work discussed above, we achieve the following improvements and contributions in this paper:

- comprehensive comparison of different fast recovery approaches, quantifying path optimality and detection overhead in addition to recovery delays
- delay impact of dynamic network reconfiguration in response to Smart Grid service requirements and network conditions, illustrated on a five step sequence of events
- delay-aware routing using NC
- compliance to hard service guarantees on basis of NC delay supervision

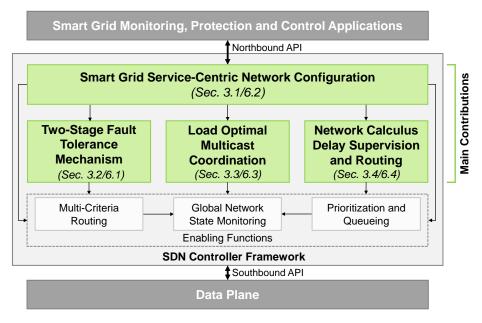


Figure 2: Elements of the Software-Defined Universal Controller for Communications in Essential Systems, their interdependencies and classification within the SDN concept (including reference to corresponding discussions)

# 3. Proposed Solution Approach for Smart Grid Communications on Basis of Software-Defined Networking

To address the challenges of communications in critical infrastructures such as the Smart Grid, we propose the Software-Defined Universal Controller for Communications in Essential Systems (SUCCESS)<sup>1</sup>. It is a Java-based framework, designed to meet hard service requirements of mission critical infrastructures. The framework was forked from the open-source Floodlight controller [40] and utilizes OpenFlow v1.3 [16].

Figure 2 illustrates the different components of our controller, including their interdependencies as well as the connection to Smart Grid applications via the Northbound Interface (NBI). As a basis for the main contributions of this work, we devise the following functions:

 $<sup>^1{\</sup>rm The}$  source code of SUCCESS is publicly available via https://gitlab.kn.e-technik.tu-dortmund.de/cni-public/success

- Global Network State Monitoring: Active traffic flows as well as link states are tracked to obtain a real-time view of the current network load.
- Multi-Criteria Routing: In contrast to standard optimal path routing, we employ Depth-First Search (DFS) to determine multiple feasible routes, which can be applied as alternatives for fast failure recovery and hard service guarantee provisioning.
- Prioritization and Queuing: For prioritization we apply a large range of priority levels, which are mapped to corresponding queues, which encompass minimum and maximum data rate guarantees on basis of Linux Hierarchical Token Bucket (HTB) [41].

We enable controller-driven, flexible queue configuration by modifying Open vSwitch (OVS) Database (DB) entries with the help of OVS commands via Secure Shell (SSH). Our SDN controller includes a dedicated module for establishing and handling SSH sessions. To avoid the overhead of repeated handshake processes, sessions are maintained and provided for reuse. According to our measurements the configuration of new queues incurs a mean delay of 273 ms (601 ms if the SSH session needs to be established). For the dynamic adaption of Smart Grid service requirements (c.f. Section 3.1), switching between existing queues is utilized. Hence, queue re-configuration is not considered time-critical.

# Control Plane Considerations

In the following, we refer to the control plane as a single instance. However, we acknowledge the need for deploying distributed or hierarchical systems of multiple controllers for large-scale real world scenarios. To achieve real-time reconfiguration of communication networks in such scenarios, utilizing multiple controllers to manage defined network partitions is inevitable [42]. Vice versa, in real-world scenarios, relying on a single controller induces the following issues: First, extending the network size would result in increasing numbers of flows to be handled by the controller. This could lead to increased calculation times

and, in case of long transmission distances, to higher delays in the distribution of SDN controller commands. In the worst case, the controller might be overloaded completely. With regard to the proposed NC routing and supervision, high numbers of flows might also compromise the feasibility of the whole approach, if computing times exceed Smart Grid delay requirements. To this end, the scalability analyses in Section 6.4.4 may indicate network partition sizes suitable for our approach. Yet, it will need to be assessed how traffic flows, traversing the domains of multiple controllers can be handled by NC routing and delay supervision. Possible approaches include exchanging intermediate calculation results or the summation of delay bounds, both building upon inter-controller communication. Also, measurement values may be integrated for this purpose.

Second, architectures with only one controller would generate a single-point-of-failure with regard to reliability and security. If the controller or the route to it fails or is compromised by an attacker, switches can fall back to a simple layer-2 operation mode [16]. However, all desired features such as hard service guarantees or the routing of new flows would be suspended. Nevertheless, as inter-controller coordination represents an entire research area of its own, we consider it out-of-scope for this work. Though, in another publication we discuss this topic with respect to control plane reliability [43].

Control plane networks are classified as either in- or out-of-band control. For our experiments, we apply out-of-band control, utilizing dedicated network links to each switch. Yet, for real-world deployments, in-band control may be better suited, as no second, parallel communication infrastructure needs to be established. In-band control may for example be realized as internal flows of higher priority [44]. Despite the fact that the peculiarities of in-band control are not evaluated in this work, we would like to stress some important preconditions:

- To ensure reliable transmission of control traffic, the controller must be connected to the data network via multiple links, protected by fast failover mechanisms.
- Control traffic needs to be estimated beforehand and kept to a minimum.

Thereby, the network's capacity can mostly be allocated to actual data traffic.

• It has to be ensured that data and control traffic do not interfere with each other, for example by using dedicated queues with appropriate priorities.

#### 3.1. Smart Grid Service-Centric Network Configuration

For adapting communication network configurations to Smart Grid specific requirements, we enable power system applications to convey their demands to the controller. Therefore, we implement the SDN NBI, using the REST API. While the controller is set up as the REST server, applications act as clients, sending requests to the controller. Interaction via the NBI is demonstrated employing the MAS as client application. Four different services – Rule Creation, Route Reservation, Flow Modification, Multicast Group Creation and their respective revocations – are provided by the controller. Details on these NBI services are provided below.

# 3.1.1. Rule Creation

Rule Creation serves to register traffic flows at the controller, disclosing their specific demands regarding minimum data rate, maximum latency and packet loss as well as priority. This information is stored at the controlled as combined flow requirements. Thus, incoming traffic can be routed and directed to an adequate priority queue, fulfilling its requirements. Hence, this functionality relies heavily on the routing, prioritization and queuing mechanisms, described previously. Applying the DELETE command in conjunction with Rule Creation removes the respective traffic rule.

#### 3.1.2. Route Reservation

Typically, in SDN-enabled infrastructures network devices contact their associated controller to request routes for newly arriving packet streams. This incurs additional delay for the first packets of a transmission. Route Reservation, however, is applied to route traffic flows and configure flow table entries in advance, avoiding this initial delay. However, such static flow table entries need to be removed explicitly, since idle time-outs are precluded.

## 3.1.3. Flow Modification

Existing flow requirements, involving priority and queue assignments, may be altered using this request. Hence, it becomes possible to raise or reduce flow priorities temporarily, e.g. in response to emergency situations. In particular, this request may be performed in case of simultaneous overloads of power and communication system. Thus, successful transmission of critical commands for relieving the power grid crisis can be ensured. Temporary changes to the flow requirements can be revoked with the help of the corresponding DELETE command.

## 3.1.4. Multicast Group Creation

We provide dedicated NBI requests, enabling Smart Grid applications to trigger generation, modification and deletion of multicast groups. To create a new multicast group, the controller is supplied with a list of Media Access Control (MAC) or Internet Protocol (IP) addresses, representing member devices. In addition, a set of header fields defines the messages, applicable for multicast transmission. Hence, the controller is able to identify multicast packets and determine appropriate routes to all destinations. The use of specific multicast addresses is not required.

## 3.1.5. Security Considerations

Though not within the scope of this work, we acknowledge the fact that securing interactions between controller, switches and applications is of critical importance. For mutual authentication on the switch-controller interface, OF provides Transport Layer Security (TLS) [16]. Similarly, for real-world application of our proposed northbound interface implementation, TLS-protected communication is required. Additionally, our concept accounts for future security enhancements such as authentication and permission systems to ensure legitimate access [45]. Otherwise, attackers could inflict damage by requesting:

- Unsuitable traffic flow configurations. For example, the priority and traffic demands of a single flow could be increased to a level that suppresses other data streams. Vice versa, flow parameters of critical Smart Grid transmissions could be manipulated to destabilize the power system.
- Fake multicast groups could be established to forward traffic to unauthorized parties.

## 3.1.6. Further Aspects of Smart Grid Adaptation

Besides the aforementioned means of direct participation, SDN provides further benefits, facilitating Smart Grid communications. As IEC 61850 is becoming a comprehensive standard for power systems, its application for wide area communications is discussed. Technical reports propose the transmission of Ethernet-based SV and GOOSE messages over IP systems, necessitating tunneling or conversion of packets to routableGOOSE/routableSV [46, 47, 48, 49]. In contrast, packet routing and forwarding in OF-enabled infrastructures builds on matches – sets of arbitrary header fields – and thus is protocol-agnostic. This allows for direct transmission of IEC 61850 SV and GOOSE messages on wide area networks.

# 3.2. Two-Stage Fault Tolerance Mechanism

Guaranteeing reliable, virtually uninterrupted, transmission is a major requirement for mission-critical communications. Therefore, mechanisms enabling fast recovery after link failures are integrated into the controller. Failover can be split into two steps: failure detection and traffic restoration. Both functions can be realized either locally at the switches or centrally, triggered by the SDN controller. To leverage the advantages of central and local algorithms at the same time, we unify both approaches to obtain a straightforward two-stage hybrid solution.

Besides complete link failures, networks may experience partial/intermittent link disruptions or high packet loss as results of malfunctioning hardware. Depending on the selected sensitivity (i.e. detect multiplier, time-out interval and

Inter-Transmission Time (ITT)), link failure detection may discover recurring link disturbances as well. Nonetheless, such configurations may lead to false positives. For identifying packet loss, on the other hand, we apply OF statistics collections. In case the number of packets lost within the collection period exceeds a predefined threshold, traffic is redirected to alternative paths, similar to link failure recovery. However, due to the associated higher traffic load, such statistics collections are typically performed in intervals of several seconds. Hence, detecting packet loss is considerably slower than link failure detection. Overall, if faulty hardware is identified, traffic may be switched to alternative paths, avoiding the affected equipment. Yet, as described above, fast detection of phenomena such as high packet loss or intermittent link behavior is more challenging compared to the complete failure of entire links. Eventually, such incidences may endanger latency guarantees.

BFD-based Local Recovery. Bidirectional Forwarding Detection (BFD) [50] is deployed to reduce failure detection times locally at the switches. It is integrated into OVS since version 2.3.0 [44] and is also applied in combination with MPLS Fast Reroute (FRR) to achieve fast recovery in MPLS-based infrastructures [51]. For monitoring a link, BFD sends lightweight messages in fixed intervals between two switches, connected via a link. If no packets from the other end of the communication line are received within a defined multiple of the packet ITT (i.e. detect multiplier), the link is assumed to have failed. Here, the ITT may be as low as 1 ms, while the usual detect multiplier amounts to 3.

Reaction to link failures, discovered by BFD, can be realized locally using OF Fast Failover Groups (FFGs). Therefore, after completing routing of a traffic flow, the controller determines alternative switch configurations for every possible link failure within the main path. These alternative configurations are stored in the switches' forwarding tables along with the main path using FFGs. Thus, in case the outgoing port of a traffic flow is reported as failed, the flow is switched to its alternative path automatically. To reduce the number of additional forwarding table entries at the switches, our algorithm is designed to

maximize the similarity between main and recovery path, letting the traffic flow return to its initial path after as few hops as possible.

SDN-driven Central Recovery. For centralized link status monitoring, we devise a heartbeat mechanism, similar to BFD, which regularly transmits lightweight probe packets. However, in this case packets are sent out by the controller, thus consuming bandwidth of control and data network. Encapsulated into OFPacketOut messages, heartbeat packets are transferred to the switches, which extract and forward the content on the monitored link. At the other end of the link, the packet is sent back to the controller using the OFPacketIn format. If this packet is not returned to the controller within a defined interval, the link is classified as failed.

In contrast to local failover, recovery paths are not pre-computed, but determined on-demand, considering current network load for obtaining load/latency optimal routes.

Two-Stage Hybrid Recovery. Local failover mechanisms usually achieve faster traffic recovery compared to centralized approaches. Yet, they might employ sub-optimal paths, resulting in network overloads. Vice versa, controller-driven recovery enables optimal traffic configuration at all times, while failover times are considerably higher. Subsequently, a hybrid approach presents an intuitive solution, combining the advantages of local and central mechanisms in a divide and conquer manner. First, BFD is employed for detecting link failures locally. Hence, traffic can be switched immediately to intact paths with the help of FFGs.

Next, the controller is notified of the failure. Subsequently, new globally optimal paths are determined and the switches' forwarding table entries are updated. Thus, fast recovery is realized, while time intervals of sub-optimal traffic flow, respectively network configuration, are minimized. To this end, independent fast local protection is combined with globally controlled restoration.

# 3.3. Load Optimal Smart Grid Multicast Coordination

Applying multicast flows allows for significant network load reductions. This is achieved by utilizing a shared path for packets from one source to multiple destinations for as long as prudent. While this concept is well-known in conventional communication networks, it is applied infrequently due to the significant effort associated with the configuration and management of multicast groups. However, this technique plays an important role in IEC 61850-based communication, being applied for the distribution of measurement values and status updates.

In this work, setup and maintenance of multicast groups is facilitated by providing direct access via the SDN NBI, as detailed in Section 3.1. The Smart Grid application simply has to provide a list of intended group members in terms of IP or MAC addresses along with a set of packet matching criteria. After reception of the first packet, which matches the multicast group, the controller performs routing and forwarding rule setup. To enable multicast handling, paths are defined as routing trees. For routing, we implemented the Bounded Shortest Multicast Algorithm (BSMA) [52], which minimizes the number of used links, while at the same time fulfilling flow requirements such as maximum delay bounds.

# 3.4. Network Calculus-Based Delay Supervision and Routing

Other than in legacy networks, where NC can be applied for offline performance evaluation only, SDN allows for utilizing this analytical technique during live operation. For this purpose, we integrate NC logic into the SDN controller to achieve – guaranteed – compliance to defined real-time requirements of Smart Grids at all times. A corresponding overview of latency demands is given in Table 1 with requirements ranging from 3 ms to more than 1 s. To pursue the goal of real-time capable communications, NC is applied for the following two use cases:

• routing of new traffic flows: provide delay-optimal paths, complying with given latency requirements

monitoring of existing traffic flows: ensure delay bound compliance,
 even when (other) flows are reconfigured or new flows are added

Before going into the details of these tasks, necessary extensions and modifications of NC are described in the following section.

#### 3.4.1. Queue Rate and Cross Traffic Extensions to Network Calculus

Complex Smart Grid infrastructures and diverse traffic flows require a detailed study of cross traffic impact as they may lead to non-feed forward behavior [53], which continues to be an issue of NC analysis [22, 54]. In addition, the influence of HTB scheduling has to be considered in NC evaluations.

Beginning with the latter aspect, we enhance our NC framework to consider minimum and maximum queue rates as introduced at the beginning of Section 3. Thus, preconditions of our testing environment are reflected. Maximum queue rates limit the sustained data rate of a flow's service curve. In contrast, minimum queue rates enhance the service available to a flow by reducing the service curves of higher priority flows, as shown by the right side of Figure 3. Equation 5 formalizes this concept for the service curve  $\beta_{k,foi}$  of a flow-of-interest foi,

$$\beta_{k,foi}(t) = \beta_{k}(t) - \sum_{q|p_{q} \geq p_{foi}} \left( \min \left( \sum_{j=1}^{\forall i \in q} \alpha_{k,i}(t), \alpha_{maxDR,q} \right) \right) - \sum_{j=1}^{\forall q|p_{q} < p_{foi} \cap \exists minDR_{q}} \left( \min \left( \sum_{j=1}^{\forall i \in q} \alpha_{k,i}(t), \alpha_{minDR,q} \right) \right),$$

$$(5)$$

with  $\beta_k$  being the basis service curve at node k. The service available to the flow-of-interest is reduced by the impact of traffic in queues q with same or higher priority  $(p_q \geq p_{foi})$ , considering the sum of respective arrival curves  $\alpha_{k,i}$  of flows i. Yet, this influence may be limited by maximum queue rates  $\alpha_{maxDR,q}$ . Additionally, flows of lower priority  $(p_q < p_{foi})$  can curtail the service by up to the corresponding minimum queue rate  $\alpha_{minDR,q}$ .

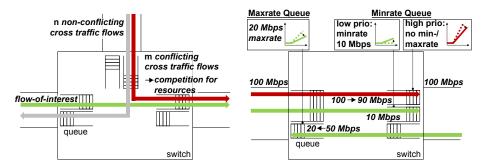


Figure 3: Extensions to Network Calculus: cross traffic handling and integration of queuing with minimum / maximum data rates

To enable the analysis of non-feed forward networks, we enhance our modeling approach as illustrated by the left side of Figure 3. In NC such systems can be assessed with the help of specialized approaches only (e.g. time stopping method), as recursive calculation of cross traffic output curves may lead to deadlocks [22]. Here, this issue is avoided by considering only those cross traffic flows, which use the same output port as the flow-of-interest. We base this modification on the assumption that interference from other traffic flows at the switches' processing unit is negligibly small. This hypothesis is confirmed experimentally – for our testing environment – by the evaluations in Section 6.4.1. In this way, analysis of cross-traffic in non-feed forward networks is converted back into a feed-forward problem. The associated definition of the left-over service curve  $\beta_{k,foi}$  for the flow-of-interest foi at node k is given by Equation 6,

$$\beta_{k,foi}(t) = \beta_k(t) - \sum_{k,i=1}^{\forall i \mid k_i + 1 = k_{foi} + 1} \alpha_{k,i}(t),$$
(6)

where the node's basic service curve  $\beta_k$  is reduced by the arrival curves  $\alpha_{k,i}$  of cross traffic, which shares the same subsequent node  $k_i + 1$  as the flow-of-interest.

#### 3.4.2. Traffic and Network Modeling

As described in Section 2.3, arrival and service curves are modeled by token bucket and rate latency representations respectively. To parametrize these curves, preliminary measurements are performed, obtaining key traffic and data processing characteristics. Service is assessed for single traffic flows as well as under full load, as shown in Section 6.4.1. In addition, the SDN controller performs continuous measurements, verifying the present modeling assumptions. To this end, OF functionalities for collecting port and flow statistics are applied. Also, information from Link Layer Discovery Protocol (LLDP) packets, utilized for topology discovery and updates, is considered. Finally, heartbeat packets from centralized fast failure detection can be put to use as well. Thus, compliance of NC modeling with the actual network and traffic performance is validated in real-time. If necessary, the controller may modify service curve parameters to adapt to changed network conditions. However, adjustments are restricted by measurement cycles and may not be sufficiently fast in case of sudden changes.

#### 3.4.3. Network Calculus Application in the SDN Controller

Figure 4 gives an overview of the aims and different steps of NC integration. On the arrival of a new traffic flow, the SDN controller applies NC-based routing to select a delay-bound compliant path. We distinguish two different approaches for this task. Using the concept of full NC routing, the new flow's NC delay bounds are determined for every path provided by the DFS. Subsequently, the path with the lowest NC delay bound is chosen. In contrast, the hybrid NC routing approach couples standard service-aware routing and NC analysis. In this way, the delay-optimal path is selected by standard routing. Subsequently, the corresponding NC delay bound is calculated for this path only. If NC analysis does not indicate a potential violation of the given latency requirement, the selected route is configured in the network. Vice versa, if NC analysis does indicate a violation, the next optimal path, provided by service aware routing, is assessed. However, this step incurs additional delay in the routing process. Eventually, if NC routing is not able to find a suitable path for the flow, it would be dropped. It has to be emphasized that this case would apply to low priority flows only, as paths chosen for high priority flows would be cleared.

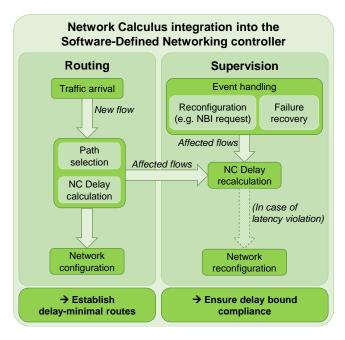


Figure 4: Concept for Network Calculus integration into the SDN controller

Meanwhile, cross traffic, affected by the new flow, is handed over to NC delay supervision. In addition, delay supervision handles flows affected by network reconfiguration. This applies for example in case of NBI-induced modified flow priorities or failure recovery. In all of the above cases, NC delay bounds of affected traffic are recalculated. If given latency requirements are exceeded, network reconfiguration is triggered. This involves measures such as rerouting and change of queues (priorities).

For both, routing and delay supervision, performance can be enhanced by re-using previously calculated output bounds of cross traffic flows. Thus, calculations are sped up, whereas the recalculation of output bounds is not time critical and can be scheduled for subsequent execution. Detailed performance comparisons of the different routing approaches are provided in Section 6.4.3.

# 3.4.4. Delay Analysis Algorithm

Algorithm 1 provides the main steps of our optimized NC delay analysis, which is applied for delay supervision and routing. The links of the intended

Algorithm 1: Network Calculus Delay Supervision Algorithm

```
Input: Flow f, path p
   Result: NC delay bound
 \mathbf{1} \ fPrio \leftarrow getPriority(f)
 {f 2} for l in getLinksInPath(p) do
      for cT in crossTraffic do
          if outputCurves.contains(cT) then
 4
              cToC \leftarrow getOutput(cT)
5
          end
6
          else
7
              cToC \leftarrow computeOutputRecursive(cT)
8
9
          end
          if getPrio(cT) > fPrio then
10
              cToC \leftarrow boundByMaxRate(cToC)
11
              highLowPrio \leftarrow add(highLowPrio, cToC)
12
13
          end
14
          else if getPrio(cT) < fPrio then
              cToC \leftarrow boundByMin(cToC)
15
              highLowPrio \leftarrow add(highLowPrio, cToC)
16
17
          end
          else
              samePrio \leftarrow add(samePrio, cToC)
19
          end
20
          markForRecalculation(cT, l)
21
      end
22
      serviceCurve \leftarrow getServiceCurve(f, l)
23
      leftoverSC \leftarrow serviceCurve - highLowPrio
24
      leftoverSC \leftarrow getFIFOService(sc, f, samePrio)
25
      scETE \leftarrow convolve(scETE, leftoverSC)
26
27 end
28 ac \leftarrow getArrivalCurve(f)
29 delay \leftarrow getDelay(ac, scETE)
30 for cT in markedDelayBounds do
      if lastLatency(cT) + TH > maxLatency(cT) then
31
          recalculateDelay(cT)
32
      end
33
34 end
35 scheduleRecalculation(markedOutBounds)
```

path are iterated sequentially and checked for potential cross traffic (lines 2-3). To reduce computation times, previously computed output curves may be used for modeling cross traffic (lines 4-6). In case of non-optimized processing, or if the curve has not been determined yet, recursive calculation of cross traffic output bounds is required (lines 7-9). They are computed up to the point of interference with the flow-of-interest. Next, cross traffic is classified with regard to its priority relative to the flow-of-interest and, if applicable, the service rate is bounded due to minimum/maximum queue rates (lines 10-20). Also, cross traffic flows are marked for output/delay bound recalculation as the flow-ofinterest influences these flows vice versa (line 21). Afterwards, the base service curve for the flow-of-interest at the current node is retrieved (line 23). Cross traffic impact is determined according to Equation 6, using the corresponding output curves with respect to their relative priority (lines 24-25). By convolving individual service curves the end-to-end bound is calculated (Equation 3). The arrival curve, in conjunction with the end-to-end service curve, serves as input for deducing the flow-of-interest's upper delay bound (lines 28-29). Finally, delay bounds of critical flows, which are effected by the flow-of-interest, are recalculated (lines 30-34) and output bound recalculation is scheduled (line 35).

Overall, NC allows for predicting and avoiding potential violations of delay bound guarantees, whereas network operation based on measurements reacts to arisen issues only. Also, measurements provide a snapshot view of the system. This might be misleading if flows show volatile behavior and measurement intervals are not sufficiently small. In contrast, increased sampling rates lead to high traffic load on the control network [55].

# 4. Smart Grid Reference Scenario and Mapping on a Corresponding Communication Infrastructure

Topology. For evaluation we use the Nordic 32 test system [10], shown on the left side of Figure 5. The system, derived from actual Swedish and Nordic systems, is well-established for power grid analysis. It spans four voltage layers from

400 kV (red lines) to 15 kV (purple lines). The system is characterized by long 400 kV transmission lines and utilizes a nominal frequency of 50 Hz. Though the test system was originally specified in 1995, it remains valid as the underlying topology is not impacted directly by recent developments towards Smart Grids. Since it maps higher voltage levels, integration of DERs is considered in terms of adjusted distribution system loads. As shown by several current publications, the Nordic 32 test system is still very relevant for power system analysis today [56, 57, 58, 59]. Further, it is supported by the fact that the Nordic 32 test system is part of the Institute of Electrical and Electronics Engineers (IEEE) Power and Energy Society's (PES) 2015 technical report on Test Systems for Voltage Stability Analysis and Security Assessment [60]. This lasting relevance of power grid test systems may be attributed to significantly longer innovation

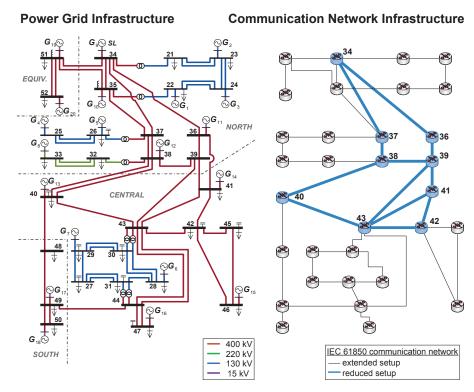


Figure 5: Mapping of the Nordic 32 Test System [10] for power grids to a corresponding IEC 61850-based ICT infrastructure

cycles [61] compared to the ICT sector. Additional details on the specifics of the system can be found in [60].

On top of this power system, we map a corresponding wide-area communication network infrastructure, shown on the right side of Figure 5. Networking devices are placed at each substation and connected using fiber-optic cables, carried along the power lines. Thick, blue lines highlight an excerpt of the network, which is modeled in our empirical testbed setup, using dedicating hardware for each network device. Scaling of the scenario to the entire network (grey lines) is achieved 1) in the testbed setup by running two virtual switches on the same server hardware and 2) by utilizing Mininet emulation [62], where applicable. Figure 6 details the small-scale testbed implementation, while Section 5 provides hardware specifications.

Traffic Pattern. Traffic patterns (number of flows, communication partners) for this evaluation scenario are generated on basis of relevant, real-world transmission grid functionalities [63, 64]. Several of these applications are already in use in today's power grids, whereas others are regarded viable for deployment in future Smart Grids. In all cases, standard protocols are considered.

SCADA incurs communication from the control center to every substation

Table 2: Traffic patterns for Nordic 32 test system

Message Type	Source(s)	Destination(s)	Number of flows in reduced (extended) experiment	Scenarios (Sections)
GOOSE	38	all	8 (31)	1-4 (Sec. 6.1-6.4)
SV SV	all all	38 neighbors	8 (31) 23 (85)	1-4 (Sec. 6.1-6.4) 1-4 (Sec. 6.1-6.4)
MMS	38	34, 42	2 (8)	2 (Sec. 6.2)
MAS MAS MAS	38 39 (further	41, 42, 43 34, 36, 43 MAS groups)	3 (3) 3 (3) (17)	2-4 (Sec. 6.2-6.4) 2-4 (Sec. 6.2-6.4) 2-4 (Sec. 6.2-6.4)
Total			47 (178)	

and vice versa to obtain measurement data and perform remote control [65]. Here, we utilize IEC 61850 communication services for this purpose, as suggested in [49]. In particular, control commands from the control center, situated at Substation 38, are sent to all substations using GOOSE messages. SV serve for exchanging measurement data with the control center as well as between neighboring substations. The latter is required for inter-substation protection functions, such as current differential protection [66]. Starting from Subsection 6.2, MAS messaging is introduced for distributed power flow control within multiple clusters of substations [67]. Also, MMS transmissions are considered for configuration and software update purposes. Though there may be additional traffic, e.g. enterprise voice and data communications, we limit our analysis to the critical functions outlined above. Table 2 sums up used traffic patterns.

Sequence of events. In addition, Figure 6 visualizes the following sequence of use cases, considering GOOSE traffic from the control center (Substation 38) to

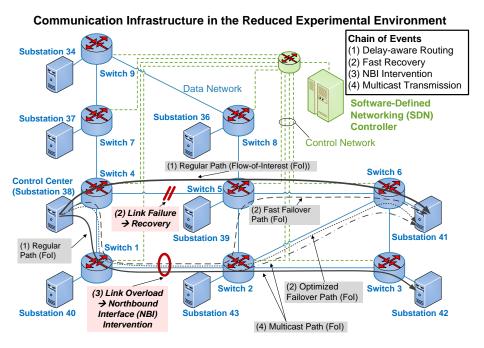


Figure 6: Reduced experimental realization of the communication network's data and control plane including use case specific paths of a flow-of-interest

Substation 41 as flow-of-interest for this analysis:

- 1. **Delay-aware routing** provides the primary path for this flow via Substations 38, 39, 41 (solid lines).
- 2. This path is interrupted by a **failure** between Substations 38 and 39, resulting in **recovery** to the fast (dashed lines) and the optimized failover path (dotted lines) (Section 6.1).
- 3. Evoked by the failure, combined with additional MAS and MMS traffic, the link between Substations 40 and 43 is **overloaded**. To maintain grid stability, dynamic **re-configuration** triggered via the **NBI** needs to be carried out (Section 6.2).
- 4. Finally, dash-dotted lines illustrate load optimization on basis of **multi- cast** transmission (Section 6.3).

## 5. Evaluation Environment for Empirical Performance Assessment

This section sums up the most important characteristics of our experimental environment as well as the used emulation software. Each experiment respectively emulation is repeated 100 times with a duration of 60 s, typically resulting in up to 6 million data points per traffic flow.

## 5.1. Experimental Set-up

Our experimental environment, shown in Figure 6, consists of three independent networks: data, control and management, created in hardware. The first network covers the data plane of the SDN architecture, representing the wide-area infrastructure for transmitting Smart Grid traffic. It includes up to 28 virtual switches (vSwitches), running Open vSwitch (OVS) v2.5.2 under Ubuntu 16.04.2 LTS (v4.4.0-77-generic x86-64 Kernel). The vSwitches are deployed on 14 servers with standard hardware (Intel Xeon D-1518 with one two port I210-LM and two four port I350 Intel 1GBase-T Ethernet Network Interface Cards (NICs)).



Figure 7: Experimental testing environment for SDN in Smart Grids

The reduced set-up is limited to four vSwitches, each run on an individual server. In comparison, for the extended environment one server is required to host two switches simultaneously. In this case, every vSwitch is assigned exclusive ports on separate NICs as well as dedicated Central Processing Unit (CPU) cores. Thereby, effective isolation of network hardware is ensured. According to [68] virtualization overheads can be classified negligible for the purposes of this work. In addition, we deploy five 48 port Picas 3290 baremetal switches (bSwitches), which utilize OVS v2.3.0 under PicOS 2.6.32. The data network is completed by seven dedicated hosts, six of which are Intel Celeron J1900 with a two port I210-LM NIC. To achieve timing precision in the range of a few microseconds, while avoiding synchronization issues, the seventh host (Intel Xeon D-1518) models Substations 38 and 41 simultaneously. Thus, corresponding measurements utilize a single clock. For mapping the entire Nordic 32 system, we additionally employed virtualized hosts on 12 servers (Intel Xeon X5650).

The SDN control plane is constituted by an out-of-band network and a

server (Intel Xeon D-1518), hosting the SUCCESS platform. Connection to the switches of the data plane is established using OpenFlow v1.3.

Finally, the management network enables remote configuration, starting and stopping of measurement processes at all hosts. Hence, it is applied for facilitating the experiment and is not part of the evaluations itself. For both, the control and the management network, one Zyxel GS1900-24E switch each provides Gigabit connectivity. Abstracting from real-world scenarios, copper instead of fiber-optic cables are employed. An overview of our testing environment is given in Figure 7 in terms of a photo of the actual laboratory set-up.

#### 5.2. Network Emulation

To validate the experimental results and conveniently scale certain aspects of evaluation (e.g. control plane performance) to the full Nordic 32 test system, network emulations are carried out. Therefore, the software Mininet [62] is run on an Intel Xeon D-1518 under Ubuntu 16.04.2 LTS (v4.4.0-77-generic x86-64 Kernel). Mininet allows for the set-up of complex, realistic network configurations, applying the same controller framework as in the experiment. Configuration is performed using the Python programming language.

# 6. Evaluation of Approaches Proposed for Mission Critical Communications

Evaluation is split into four parts, each highlighting different hard service guarantee aspects, introduced in Section 3.

## 6.1. Comparison of Fast Failover Approaches

Within this subsection, we compare the failure detection and recovery mechanisms, described in Section 3, with regard to recovery delays, route optimality and induced network load. Bidirectional Forwarding Detection (BFD) was configured with an Inter-Transmission Time (ITT) of 1 ms and a detection multiplier of 3, whereas the controller Heartbeat (HB) does not stabilize until an ITT of 3 ms, timing out after 15 ms. A link failure between Substations 38 and

39 is produced, interrupting the GOOSE traffic flow from the control center to Substation 41.

#### 6.1.1. Recovery Delay Evaluation

Figure 8 depicts the flow's end-to-end recovery delays, measured at Substation 41 in our testbed set-up (c.f. Figure 6). End-to-end recovery delay refers to the time difference between the last packet received before the failure and the first packet received after clearance. It can be seen that recovery delays depend significantly on the detection mechanism applied. Using BFD traffic is switched to an alternative path within 4.73 ms at maximum.

In contrast, controller centric failure detection and recovery requires up to 33 ms. Yet, this approach redirects the GOOSE traffic flow to an optimal path directly, whereas applying Fast Failover Group (FFG) in combination with BFD necessitates subsequent optimization. This step may be triggered in response to the reception of regular OFPortStatus messages, which is not until approximately 350 ms after the failure [9].

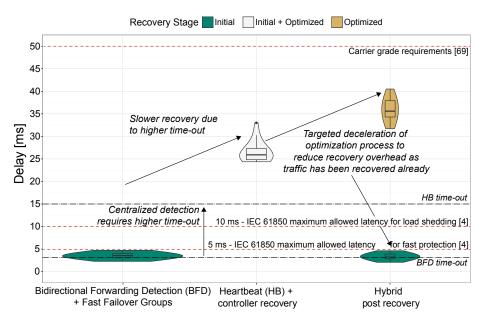


Figure 8: Comparison of initial and optimized recovery delay for different approaches using Software-Defined Networking

Integrating the advantages of both approaches, the hybrid approach uses BFD and FFG for immediate recovery, achieving the same latencies. In a second step Heartbeat (HB) messages are used to initiate controller-based post optimization with a mean delay of 35.94 ms. This value is close to the recovery delay of the controller centric approach. To minimize network load of the hybrid approach, the HB interval for post optimization is increased to 10 ms. This choice is a trade-off between fast optimization of routes and reduced data and control network load. Using this parameter set, optimization is executed within about 40 ms at maximum. Thus, carrier grade requirements (50 ms) [69] are fulfilled, while considering a security margin of 10 ms. Faster optimization could be achieved by applying the same values as for controller-driven recovery (c.f. restrictions above). In contrast, further load reduction could be enabled by increased ITTs and time-out intervals. For example, when striving for the IEC 61850 requirement of 100 ms for slow automatic interactions, the ITT might be raised to 25 ms (detect multiplier: 3). Further details on load reduction are discussed at the end of this subsection.

#### 6.1.2. Path Optimality

Figure 9 illustrates the aspect of path optimality, considering the criteria minimum hop count (left side) and load balanced network links (right side). This study utilizes Mininet emulation (hop count), respectively the extended hardware set-up (network load), to study the entire 75 link communication network of the full Nordic 32 system. The results of regular routing, before the failure, serve as benchmark for both cases. The left-side of Figure 9 visualizes the increase to a maximum hop count of eight due to FFG recovery. In comparison, the maximum hop count in case of controller recovery amounts to six only. According to the right side of Figure 9, the median network load is reduced from 22 Mbps in case of FFG paths, to 20 Mbps after controller recovery respectively post optimization. This effect is highlighted even more clearly by reduced upper and lower quartiles.

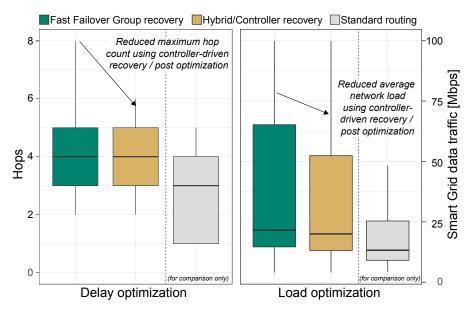


Figure 9: Hop counts and network load before/after failover using different Software-Defined Networking-enabled recovery methods

### 6.1.3. Link Load Assessment

Table 3 sums up the additional network load induced by the different failure detection mechanisms. Link respectively network utilizations  $\eta$  are determined analytically for the monitoring of the entire 75 link Nordic 32 system, using the straightforward approach given in Equation 7:

$$\eta = \frac{p}{ITT} \cdot \frac{n}{R} \tag{7}$$

where for the control network the maximum of OFPacketIn and OFPacketOut message (encapsulating the heartbeat message) is used as packet size p. Raw Ethernet packet size of BFD/HB messages is applied for the data link. R refers to the offered network capacity and n indicates the number of monitored links in case of the control network load. For the data network, each link is considered individually, resulting in n = 1.

While the controller HB achieves the lowest data network load of 0.017%, its frequent transmissions back to the SDN controller require 3.360% of the control

Table 3: Continuous additional load due to failure detection mechanisms on 75 data network links with 1 Gbps capacity each and 1 Gbps control network

Recovery Approach	Data Network			Control Network			
	ITT [ms]	Packet Size [Bit]	Load [%]	ITT [ms]	Packet Size [Bit]	Load [%]	
BFD	1	560	0.056	-	-	0	
Controller- Heartbeat	3	512	0.017	3	1,344	3.360	
Hybrid	1/10	560/512	0.061	10	1,344	1.008	
Hybrid optimized	1	560	0.056	-	-	0	

network capacity, which is the highest demand among all approaches. In comparison, even the hybrid approach, which comprises less frequent HB messages, incurs a control network load of just 1.008 %. However, a slight increase in data network load to 0.061 % has to be noted. Finally, the data network load of BFD is in between the other two approaches, whereas the control network is only stressed in case of failure. Further optimization of the hybrid mechanism, may reduce its associated network loads to the same levels as those of BFD. Overall, the load on the monitored link is comparatively low in all cases (< 0.1%). In comparison, the control network could experience considerable stress, depending on its topology and the number of monitored links. Additionally, assuming adequate processing resources being available to the controller, it needs to be highlighted that scalability of the recovery approaches boils down to the issue of control network utilization. Corresponding loads are observed to be minor in this work, as a result of applying out-of-band control. In contrast, it might become a more severe issue, when in-band control is employed in real-world scenarios. Hence, in such scenarios hybrid fast failover should utilize reduced ITTs or the hybrid optimized failover, relying on BFD only.

All in all, the hybrid recovery concept can be considered a reasonable compromise between low recovery delays, path optimality and consumed network capacity. The latter is even improved by an optimized version of the approach.

## 6.2. Smart Grid Service-Driven Dynamic Priority Adaption

Using the example of varying service requirements for Multi-Agent System (MAS)-based distributed power grid control, dynamic adaption of network configurations is shown. This involves prioritization, queuing and Northbound Interface (NBI) requests. A five step sequence of dynamic prioritization tasks is executed, as shown in Figure 10. The sequence involves two of the NBI requests, introduced in Section 3.

In step 1, MAS traffic is transmitted on an empty link between Switches 40 and 43. In total, these MAS messages have a capacity demand of approximately 5 Mbps, illustrated by bar plots in the upper part of Figure 10. This results in mean latencies of  $351 \,\mu\text{s}$ , depicted by the violin plots in the graph's lower part.

Next, normal traffic conditions, as described in Section 4, are restored. Hence, GOOSE and SV traffic are present on the network as well. Further, additional MMS traffic for the purpose of updating devices is injected into the

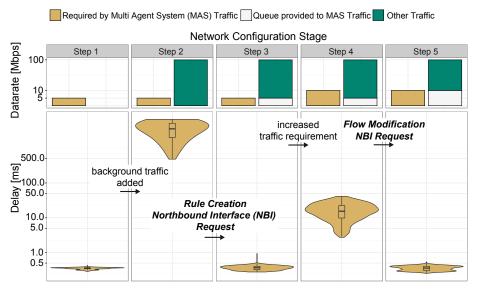


Figure 10: Successive steps of handling Multi-Agent System (MAS) traffic in response to changing network conditions, Northbound Interface (NBI) requests and subsequent priority/queue assignment

ICT infrastructure. In conjunction with the link failure, discussed in the previous subsection, this leads to an overload of the communication link between Substations 40 and 43 as shown in step 2 of Figure 10. Since MAS traffic is not recognized by the controller yet, it is handled as best effort, causing a drastic increase of the delay of up to 6.76 s.

To resolve this issue, a Rule Creation request is sent. Thus, the MAS priority is raised to 30, which is well above the priority of MMS (priority level 20). Adequate queues with 5 Mbps minimum data rate are arranged for. Hence, delays are reduced back to below 1 ms, as shown in step 3.

Next, due to the power system being highly loaded and not in (N-1) secure state, an outage occurs, disconnecting the transmission line between Substations 38 and 39. Subsequently, parallel transmission lines between Substation 40 and 43 become overloaded. This emergency situation is identified by the agents of the distributed control system. To prevent cascading outages, the MAS aims at estimating the grid state on basis of refined measurement data. Accordingly, its monitoring precision has to be improved. Building on the detailed view of the power system, adequate counter-measures can be determined, which – in this case – involves triggering a Power Flow Controller (PFC). These developments lead to more frequent transmissions of critical MAS messages, thus increasing the traffic load, as shown in step 4 of Figure 10. However, the queue assigned to MAS messaging is not sufficient for these altered data rate requirements, causing a rise in delay up to 41.43 ms.

Subsequently, a Flow Modification request is issued to obtain a temporary raise of priority. Thus, MAS traffic is switched to a higher priority queue, providing up to 10 Mbps minimum data rate and restoring the initial delay level (step 5 of Figure 10). In this way, despite of the heavily loaded communication network, timely transmission of critical control messages can be ensured. In turn, power system stability can be maintained, preventing cascading outages.

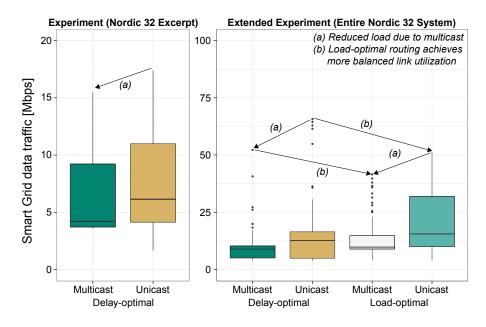


Figure 11: Comparison of network load using uni- and multicast flows in simulation (left) and experiment (right)

# 6.3. Validation of Multicast Load Reduction

This subsection targets load reduction with the means of multicast transmission. Therefore, transfer of measurement values and statuses from one to multiple other substations is bundled in multicast transmissions, wherever possible. In addition, if identical commands are sent by the control center to several substations, these GOOSE messages are transferred as multicast. On shared paths between different agents of the distributed control system joint transmission is employed as well. The resulting optimization of bandwidth consumption in the network is studied using experiments.

Figure 11 (left side) contrasts network utilization for unicast and multicast transmission, measured in our testbed. Compared to unicast, the mean link load is reduced from  $7.50\,\mathrm{Mbps}$  to  $6.63\,\mathrm{Mbps}$ . In addition, applying multicast diminishes the maximum load by  $11.1\,\%$  to  $15.47\,\mathrm{Mbps}$ , shown by marker (a).

Scaling up, the extended experimental set-up is used to study the impact of multicast on the whole 75 link Nordic 32 system. While in the reduced testing

environment we focus on delay optimal routing, the extended measurements include load optimal routing as well. Figure 11 (right side) shows link loads for the four different combinations of uni-/multicast transmission and delay/load optimal routing. Similar to the previous experiments, a reduction of mean and maximum load is observed, when exchanging unicast for multicast transfers, highlighted by marker (a). This holds true for both routing disciplines. Comparing the different routing schemes – among each pair of unicast respectively multicast transmissions – shows an increase of mean link utilization for load optimal routing. In contrast, the maximum load is delimited to a lower level as can be seen from marker (b). This behavior matches perfectly the concept of balancing network utilization.

## 6.4. Evaluation of In-Controller Network Calculus Supervision and Routing

As described in Section 3.4, we apply Network Calculus (NC) for delay-aware routing of traffic flows and online supervision of latency requirement compliance. In the following, prerequisite evaluations are performed for assuring the assumptions of modified cross traffic handling. Next, calculated NC delay bounds are cross-validated against the results of empirical measurements. This section concludes with evaluations on the applicability and optimization of NC-based routing and delay supervision.

### 6.4.1. Prerequisite Assessment of Cross Traffic Handling

Preliminary studies for NC application include the analysis of switching delays of a virtual switch for different ITT and traffic conditions, as illustrated in Figure 12. It needs to be stressed that these evaluations only serve for confirming the assumptions on cross traffic behavior described in Section 3.4. They do not reflect actual traffic configurations considered in the remainder of this article.

To deduce latencies, traffic captures of one specific flow-of-interest at the ingress and egress port of the switch are considered. The single traffic flow case constitutes a scenario, in which only the flow-of-interest is present, whereas in

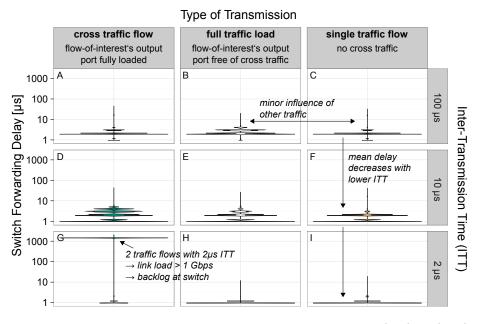


Figure 12: Traffic flow switching delay for different Inter-Transmission Time (ITT) and (cross) traffic conditions on a  $1\,\mathrm{Gbps}$  network

the cross traffic case a second flow uses the same egress port. The full traffic load scenario involves additional communication streams, reaching the switch, however obviating the egress port used by the flow-of-interest. It can be observed that the delay decreases with reduced ITT (for a more detailed analysis of this phenomenon c.f. [70]). Meanwhile, additional traffic at the switch shows minimal influence on the switching performance, if different egress ports are used. In comparison, cross traffic being present on the same egress port, evokes rising delays of the flow-of-interest. If the competing traffic flows exceed the maximum capacity of the connected egress link – which is true for an ITT of  $2 \mu s$  – delay even increases by three orders of magnitude (c.f. Figure 12.G). Accordingly, traffic using the same output port as the flow-of-interest needs to be considered for delay analysis due to its significant impact, whereas the influence of traffic flows on other output ports has been shown to be negligible. Hence, NC can be simplified in this regard, as described in Section 3.4. This obviates the issue of looped flow dependencies, which otherwise might cause deadlocks

in computation [53]. On the other hand, measurements reveal the need for considering the impact of varying ITT on switching latencies. Subsequently, these findings are integrated into NC.

# 6.4.2. Validation of Network Calculus Delay Bounds

In the next step, we aim at comparing measured network delays to the results of NC-based flow analysis in order to prove its applicability for network state monitoring and delay supervision. Figure 13 comprises measured delays in terms of violin and box plots for GOOSE and MAS transmissions between the control center (Substation 38) and Substation 41, considering three different scenarios. Above the violins, dotted lines indicate the maximum measured delay, whereas solid lines represent the corresponding results of in-controller NC analysis. In comparison to the previous evaluation, the traffic loads listed in Table 2 are restored. Hence, the two flows-of-interest are interfered by multiple cross traffic flows.

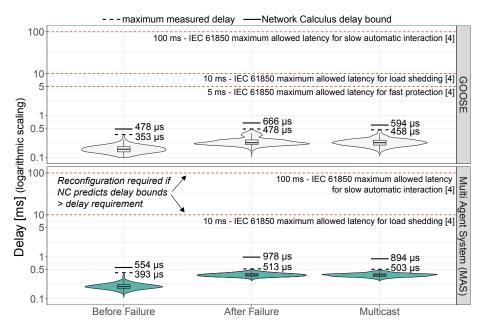


Figure 13: Measured delays (violin plots, box plots, dashed lines) and Network Calculus (NC) bounds (solid lines) of GOOSE and Multi-Agent System (MAS) traffic from Substation 38 to 41 for different scenarios

The scenarios considered map to the use cases presented in the course of this paper: before failure of the communication link between Substations 38 and 39, after failure recovery to alternative paths and after applying multicast transmission mode. Dynamic prioritization is excluded here, since it would involve overloading communication links, resulting in infinite delay bounds in NC.

In all three scenarios, NC bounds are not exceeded, being 120 to  $450\,\mu s$  above the maximum values, measured in the testbed. Deviations between NC bounds and maximum measured values increase for the case of MAS traffic after occurrence of the ICT failure. This effect can be attributed to NC's sensitivity to prioritization. In this case, the behavior is sparked by relatively low priority of the MAS service in combination with numerous – higher priority – cross traffic flows, being present on the back-up route. Nevertheless, evaluation highlights that NC provides valid means of network latency estimation within SUCCESS. Delay bounds are found to be well-above maximum measurement results, while not being overly loose. Yet, it needs to be kept in mind that real-world systems might be extremely dynamic, experiencing sudden, unforeseen changes in delay or available bandwidth. Unfortunately, NC computation is not able to account for such situations directly. However, there are two approaches to handle this challenge:

- Periodic measurements can be used to ensure the validity of service and arrival curve models, as described in Section 3.4.2. Yet, reasonable update intervals – considering the induced additional network load – might not be sufficient to handle sudden events.
- Due to its pessimistic nature (i.e. being based on worst case assumptions [22]), NC includes a certain degree of tolerance against the impact of unforeseen events.
- In addition, a threshold (c.f. Algorithm 1) is introduced to ensure timely controller intervention. Thus, actions are taken before NC delay bounds

actually reach admissible delay requirements. In this way, the consequences of unforeseen factors can be compensated for. Here, we consider a threshold of  $10\,\%$ . Measurements in real-world environments might be utilized to optimize this value.

In addition, the evaluations performed in this section provide an example of validating desired delay guarantees against the outcome of the established network configuration on basis of measurements. Additional comparisons were conducted for all flows in the scenario. However, this validation is performed offline. In an extension of our approach, such measures might be integrated in terms of a real-time feedback loop.

# 6.4.3. Evaluation of Network Calculus-based Routing

Figure 14 compares the performance of NC based routing with the computation times of our regular, service-aware routing approach. While the regular routing completes within less than 3 ms at maximum, full NC-based routing incurs mean delays of 14.44 ms. Computation speed of this NC routing approach

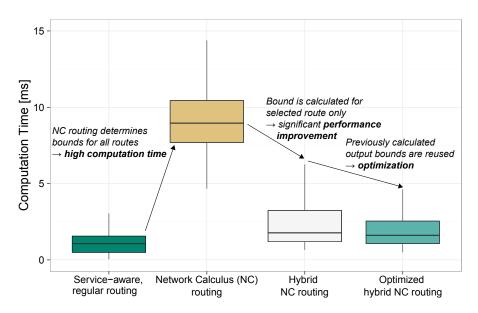


Figure 14: Comparison of computation times for regular, Network Calculus-based and hybrid routing approaches, used in our Software-Defined Networking (SDN) Controller

is determined by the fact, that delay bounds are derived for all feasible routes within the full Nordic 32 communication network. The performance of our algorithm might be improved by parallelizing calculations, e.g. assessing different routes simultaneously.

In contrast, the hybrid NC routing concept builds on the idea of coupling service-aware routing and NC analysis. Therefore, an optimal route is determined using regular routing, for which delay bound compliance is checked with the help of NC. Hence, performance is improved to mean computation times of 2.66 ms. To further optimize computation times of NC routing, we re-use previously calculated output bounds during delay bound calculation for the new flow-of-interest as described in Algorithm 1. This obviates efforts of recursively determining output bounds on-the-fly. Subsequently, the mean calculation period is decreased to 2.17 ms in case of optimized hybrid NC routing, however at the cost of reduced precision of the delay bound.

# 6.4.4. Optimization of Network Calculus Computation Times

The following evaluation focuses on the optimization of NC computation times for the application within the SDN controller. The performance of the baseline algorithm and the optimized approach are compared in Figure 15, displaying measured computation times for the complete Nordic 32 system. The baseline algorithm was utilized for NC and hybrid NC routing, whereas the enhanced version has been employed for optimized hybrid NC routing as well as for NC delay supervision. Following the baseline approach, output bounds of all cross traffic flows are computed on-the-fly during delay calculation of the flow-of-interest (first column). This leads to maximum computation times of 76 ms. Afterwards, the delay of all previously installed traffic flows is recalculated, considering the impact of the new flow (second column). This step may take up to approximately 1 s.

Initial delay analysis of the flow-of-interest can be sped up by making use of previously calculated output bounds. Thus, calculation times can be reduced to maxima of 10 ms for the flow-of-interest and 50 ms for affected cross traffic

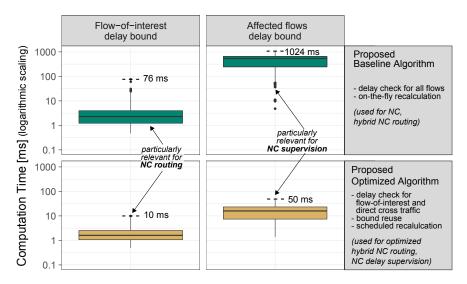


Figure 15: Comparison of computations times for different calculation objects and algorithms with relevant parameters for NC routing respectively NC delay supervision being highlighted

flows. The latter provides a worst-case estimation as delay bounds for all cross traffic flows are recomputed. In real-world scenarios it would be sufficient to recalculate the delay bounds of those flows close to their respective latency requirements. Due to the concept of reusing existing output bounds, it becomes necessary to perform a third calculation step, recalculating the output bounds. Nevertheless, this final step does not need to be executed immediately, but may be scheduled.

This evaluation is complemented by the scalability analyses, provided in Figure 16. For this purpose, maximum computation times of the two proposed algorithms are displayed for both applications, i.e. routing and delay supervision. On the x-axis network size is varied in terms of increasing numbers of interconnected nodes. In the previous scenarios, we applied a realistic communication network topology based on the Nordic 32 reference power system. However, for investigating scalability, we utilize the Barabási-Albert model [71] to generate random graph topologies. Based on these network scenarios, rising numbers of random traffic flows are created, illustrated by the sets of curves in Figure 16. To obtain adequate results, the evaluations are performed for 100

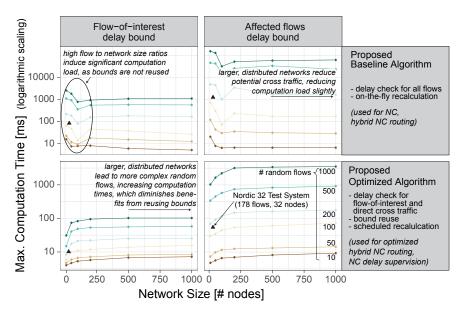


Figure 16: Scalability of NC algorithms, integrated into the SDN controller, with regard to computation times, when varying network sizes and numbers of flows

different seeds of the random number generator, providing different topologies and flow configurations. Each of the four fields in Figure 16 contains a triangle symbol, which represents the corresponding results of the Nordic 32 system.

Similar to the evaluations in Figure 15, it is apparent that the proposed optimized algorithm outperforms the respective baseline approach. For example, delay bound calculations for the flow-of-interest in NC routing may require up to approximately 1 s (1000 flows, 1000 network nodes), when applying the proposed baseline algorithm. Using the optimized approach, computation times can be reduced to about 100 ms for the same configuration. Overall, for all approaches and applications, computation times increase with rising numbers of considered traffic flows.

However, with regard to network size, the curves of the two algorithms indicate different scaling properties. In case of the optimized algorithm, computation times experience logarithmic growth with increasing network size. The approach profits from very small networks with several flows sharing the same paths. Thus, the gain from reusing previously calculated bounds is maximized.

By extending the topology, the advantage declines as the random flows become ever more complex, leading to significantly higher computation times. Nevertheless, when the network size is further increased this effect is balanced, as flows are less likely to interfere. Hence, the rise of computation times is weakened.

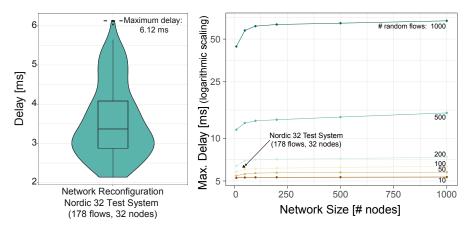
In contrast, small network topologies can be seen as a worst case scenario for the proposed standardized algorithm. In such systems, especially under high loads, interference between traffic flows is maximized. Similar delay bounds have to be computed repeatedly, as there is no re-use of existing bounds. Subsequently, computation times drop with increasing network sizes due to reduced interference. Though, when the topology is further extended, similar effects as for the optimized approach apply. Thus, computation times experience another rise. However, for very large systems, the balance between the different effects shifts. Enhanced distribution of traffic flows among the network leads to slight reductions of computational loads.

Besides comparing NC algorithms, Figure 16 points out limitations of our proposed routing and delay supervision concepts. To comply with IEC 61850 service requirements, the area supervised by a single controller needs to be confined to a certain combination of network nodes and flows. For example, up to about 100 flows may be managed on topologies of up to 1000 nodes. In contrast, orchestrating 200 transmissions requires restricting the network to about 50 nodes. This investigation is continued in the following section.

#### 6.4.5. Assessment of Delay Supervision for Dynamic Reconfiguration

Finally, the application of NC delay supervision in the context of dynamic network reconfiguration is evaluated. As shown in Figure 4, reconfiguration may be caused by the insertion of new traffic flows, as direct and indirect result of NBI requests or evoked by failure recovery. In this context, Figure 17a comprises measurement results for the delay of network reconfiguration in terms of a violin and overlaid box plot. The median reconfiguration time amounts to 3.37 ms, whereas at maximum delays of 6.12 ms are reached.

Analogous to Figure 16, Figure 17b assesses scalability in terms of maxi-



(a) Nordic 32 system measurements (b) Scalability analysis using random topologies, flows

Figure 17: Delay incurred by network reconfiguration

mum reconfiguration times, depending on network size and number of flows. Supporting the results of the previous evaluations (c.f. Section 6.4.4), it is shown that the number of flows is a particularly limiting factor for dynamic network reconfiguration. In comparison, the impact of network size is minor. Considering IEC 61850 latency requirements, the reconfiguration of up to 200 flows is regarded as manageable. The obtained reconfiguration times are taken into account for subsequent analyses.

Table 4 focuses on the case of NBI request-induced network reconfiguration, comparing delay impact of different implementation options. These alternatives deviate with regard to the order, in which processes are executed. In case of post-reconfiguration check the network configuration (queue rate, priority) is altered immediately, resulting in maximum adjustment latencies of about 12 ms for the requesting flow in the Nordic 32 reference system. Only afterwards, NC is employed to recalculate the delay bounds of affected flows and check for potential violations of given latency requirements. If so, subsequent reconfiguration of the affected traffic flows has to be performed. Accumulating NC computation and corresponding reconfiguration times, a worst case delay of 56 ms is constituted.

In contrast, using the pre-reconfiguration check other flows are not influ-

Table 4: Delay impact of computation times derived from the results presented in Figures 15, 16 and 17

Options	Chain of	Max. Delay impact [ms]					
	Events	Request. flow			Affected flows		
	Flows Nodes	178* 32	100 1000	200 100	178* 32	100 1000	200 100
Post-reconfiguration check	1. Request	6	6	6	-	-	-
	2. Reconfiguration of requesting flow	6	6	6	-	-	-
	3. NC recalculation	-	-	-	49	72	92
	4. Reconfiguration of affected flows	-	-	-	6	6	9
	Total	12	12	12	56	78	101
$\rightarrow$ in the worst ca	se, affected flows impac	cted cor	nsiderab	oly			
Pre- reconfiguration check	1. Request	6	6	6	-	-	-
	2. NC recalculation	49	72	92	-	-	-
	3. Reconfiguration of affected flows	6	6	9	-	-	-
	4. Reconfiguration of requesting flow	6	6	6	-	-	-
	Total	68	90	113	0	0	0
$\rightarrow$ in the worst ca	se requesting flow impa	acted co	onsidera	ably			
* *	Smart Grid services wit controller partitions	h laten	icy req	uirem	$ents \ge$	100 ms,	

<sup>\*</sup>Nordic 32 reference system

enced by the NBI request as potential effects on their delay bounds are assessed beforehand. However, in this way the reconfiguration of the requesting flow is delayed by up to 68 ms in the Nordic 32 system. Hence, both approaches exhibit advantages and disadvantages, either for the requesting flow or for affected transmissions. Further, Table 4 comprises two additional network and flow configurations taken from the evaluations in Figures 16 and 17b. The second parameter set (100 flows on 1000 nodes) allows reconfiguration times just below 100 ms, whereas the third (200 flows on 50 nodes) yields latencies slightly above this value. Taking into account Smart Grid latency requirements defined in Table 1 as well as the different network configurations investigated (c.f. Figures 16 and 17b), the following conclusions can be drawn:

- Combining NC delay supervision with dynamic network reconfiguration allows for flexibly reallocating resources for Smart Grid traffic flows with latency requirements ≥100 ms as delay compliance is ensured at all times. However, the network partition supervised by a single controller needs to be limited in size and number of flows. Feasible extrema of configuration are the following: up to 100 flows and 1000 nodes or up to 200 flows and 10 nodes. Besides, there are further possible combinations in between.
- In contrast, extremely time critical services with latency requirements <10 ms may not be subjected to reconfiguration at any time.
- Vice versa, minimum and maximum queue concepts have to be employed for assuring dedicated resources for these services. Respective configurations must not be altered during failover or reconfiguration.
- Further optimization of algorithms and hardware set-up may enable extending dynamic, NC monitored network reconfiguration to Smart Grid services with latency requirements of 10-100 ms. Currently, feasible network configurations range from 10 flows and 200 nodes to 50 flows and 10 nodes.

Overall, the evaluation results highlight that applicability and performance of NC routing and delay supervision are tightly coupled to the dimensioning of network partitions, i.e. the areas orchestrated by one controller. At the same time, these interdependencies raise the issue of coordinating NC operations between multiple controllers.

# 7. Conclusion and Future Work

To cope with the complex challenges of mission critical communications in cyber-physical systems, we proposed the use of Software-Defined Networking (SDN) on basis of our Software-Defined Universal Controller for Communications in Essential Systems (SUCCESS) framework. In this article we focused on the case of emerging Smart Grid infrastructures, evaluating the suitability of

our approach with the help of experiments and emulations. Therefore we modeled an ICT infrastructure on top of the well-established Nordic 32 test system and derived specific scenarios for each aspect of hard service guarantees.

Reliability of communication networks was studied with regard to handling critical link failures. Applying a hybrid concept, combining distributed and centralized failure detection and recovery, maximum delays of 5 ms are achieved, while maintaining optimal paths almost continuously.

Dynamic adaptation of priorities (queues) is utilized for minimizing communication delays of a Multi-Agent System (MAS), even in the presence of high traffic load. Alternating requirements are conveyed via the controller's Northbound Interface (NBI), relying on the REST API. In addition, the NBI is used for creating multicast groups, as commonly used in IEC 61850 communications, significantly reducing average and maximum link load.

Finally, the analytical modeling approach of Network Calculus (NC) was integrated into SUCCESS and tailored to the specifics of min/max rate queuing as implemented at the switches within our testing environment. Hence, real-time capability of critical communications can be monitored online on basis of hard worst case delay bounds. In case of violations, remedial actions, such as fast re-routing or dynamic priority adaptation, are applied. In contrast to measurement-based latency supervision, NC integration enables a comprehensive view on delays, their triggers and even predictions of future endangerments. Yet, we also indicated limits of NC-monitored dynamic network reconfiguration as – for numerous traffic flows – computation times may jeopardize latency requirements of extremely time critical Smart Grid protection functions (<10 ms). Further, NC was utilized for improved, delay-bounded routing.

Further enhancing our reliability concept, subsequent work will deal with fast failure recovery for multicast traffic flows. Moreover, we aim at establishing communication between distributed, inter-connected controllers in order to achieve a) controller resilience and b) improve the scalability. With respect to the latter, the realization of NC-enabled routing and delay supervision in infrastructures, with individual controllers for different network partitions, presents

an interesting field of further research. Major challenges include the handling of traffic flows, traversing multiple controller domains. Additionally, assignment of transmission capacities in wireless networks can be added to the controller's capabilities.

# Acknowledgement

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