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Intertwined: Software-Defined Communication Networks for Multi-Agent System-based Smart Grid Control

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***Abstract*—Facing current and future developments of the energy system, including the integration of large numbers of renewable energy sources and electric vehicles, live monitoring and control becomes essential for stable operation of the power grid. This transition to a Smart Grid requires coupling the power system with a reliable and real-time capable communication infrastructure. In response to this demand, we propose a combined approach for the control of power and communication systems, exploiting the opportunities of Software-Defined Networking (SDN). Due to its real-time capability, a Multi Agent System (MAS) is applied for controlling power flows, handling overloads and guaranteeing voltage stability in a decentralized manner. The MAS is supported by an Information and Communication Technologies (ICT) infrastructure, which follows the paradigms of SDN by applying a programmable controller platform with global network view to orchestrate traffic flows. To meet specific requirements of the MAS, we implement an SDN Northbound Interface, enabling control agents to communicate with the SDN controller directly. Thus, agents can advertise their demands to the controller, which translates them into corresponding forwarding rules and establishes them in the network. By applying fine grained prioritisation and integrating MAS and SDN controller, we showcase reliable and timely transmission of critical command messages, thereby ensuring power grid stability.**

I. INTRODUCTION

Evolving current power systems towards Smart Grids, integrating renewable, Distributed Energy Resources (DER), results in massive changes in energy generation, transmission and distribution [1]. In particular, measures like energy storage, e.g. using Electric Vehicles (EV), and real-time adjustment of generation and load are required to cope with induced volatile feed-in. Addressing these challenges necessitates precise monitoring and control of the energy system, backed by a reliable and real-time capable ICT infrastructure [2].

In this paper, we propose a Multi-Agent System (MAS) for grid control, coupled with a software-defined Smart Grid communication network, as shown in Figure 1. Contrary to centralized concepts, the MAS achieves real-time grid control in case of sudden and unexpected system faults [3], with agents sited at each substation of the transmission grid. They communicate with nearby agents, exchange measured data and coordinate actions preventing voltage collapse or line overload. On the other hand, Software-Defined Networking (SDN), on basis of OpenFlow [4] offers an innovative solution for communication in energy systems, relying on dynamic, flexible network configuration and control, implemented via a programmable controller platform. In comparison to traditional networking approaches, SDN allows linking various functionalities like fast failure recovery and prioritisation. Thus, critical measurement data and control commands can be identified, prioritised and transmitted according to their specific requirements. By establishing an interface between agents and SDN controller, close integration of both systems is achieved, enabling fine grained adjustment to varying MAS traffic demands and ensuring real-time grid control at all times. The remainder of this paper is structured as follows: Section II compares the proposed concept to other approaches of MAS based power grid control respectively software-defined Smart Grid communication networks. In Section III, we introduce the set-up of our test environment. Next, the concepts of MAS and SDN-driven ICT infrastructure are outlined in Section IV, followed by a detailed description of their combination. Subsequently, the scenarios and corresponding evaluation results are presented in Sections V and VI. The paper is completed by a conclusion and an outlook on future work (Section VII).

II. RELATED WORK

In recent years, MAS were of great interest in research for various applications. Regarding voltage stability, in [5] a

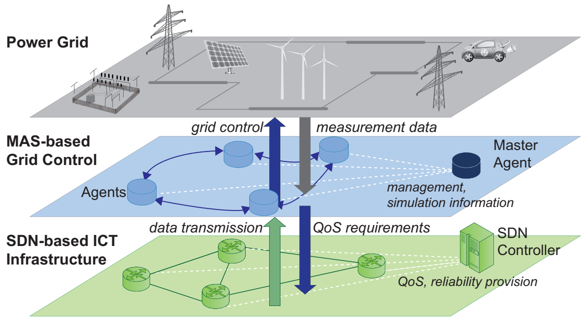

Figure 1: Combined Architecture of Power Grid, Grid Control and ICT Infrastructure

MAS was developed for improving dynamic voltage stability of distribution networks using distributed static synchronous compensators. Islam et al. [6] developed a MAS based algorithm for voltage collapse prevention in multi-area power systems, where an optimal solution is found by decomposing the optimality condition and solving it with the help of the individual agents. Also, MAS have been used for power dispatch of distributed generation [7]. In our case the MAS coordinates power flow controlling devices or initiates redispatches as corrective actions in emergency situations [3][8]. In contrast, this work focuses on communication solutions for the MAS. With regard to software-defined Smart Grid communication networks, there are a couple of works, studying the suitability of SDN for this particular use case. Cahn [9] and Molina [10] focussed on self-configuring IEC 61850 substations, enabled by SDN. In [11] SDN was used for adapting measurement data traffic, generated by phasor measurement units, to the capabilities of receiving devices. Sydney [12] evaluated the performance of applying OpenFlow in Smart Grid communications in comparison to Multiprotocol Label Switching (MPLS) simulatively. Concerning the SDN *Northbound Interface* (*NBI*), a great variety of implementations exists but, as pointed out in [13], so far no standard approach has emerged. The majority of works regarding the *NBI* deal with general functionalities like monitoring and QoS configuration [14] or focuses on use cases such as cloud computing [15] or Internet/multi media applications [16]. In comparison, our SDN-based approach provides dynamic QoS configuration for critical power grid control via the MAS.

III. TEST ENVIRONMENT

This section describes our test environment, as depicted in Figure 3, giving the individual components' characteristics.

A. *Multi Agent System*

The here presented MAS builds on the Java Agent DEvelopment (JADE) framework, which provides Java libraries facilitating the implementation of agent systems. JADE complies to the Foundation for Intelligent Physical Agents (FIPA) specifications, which define standards assuring agent system interoperability, by including, e.g. rules for agent communication. MAS created on basis of the JADE libraries are build following a well-defined structure of agents, containers and platforms. Every JADE platform consists of one or more containers, which in turn host a number of agents. The basis of each JADE platform is a main container, holding agents for platform management. The JADE framework can be executed in a distributed manner on several disparate physical hosts. To recreate distributed power grid control, we distribute the agents of our MAS on individual hosts within the communication network, each representing a substation of the transmission grid. Thus, agent communication and its effect on power grid control can be analysed in a realistic manner. Here, the power system behaviour is simulated with the help of DIgSILENT PowerFactory. Simulation results and decisions of the MAS are exchanged via an OLE for Process Control (OPC) interface between the simulation and a central master agent, which distributes data to and collects decisions from other agents.

B. *SDN Testbed*

The SDN testbed consists of six data plane switches, two of which are bare metal devices, while the remaining four use standard computing hardware running Open vSwitch [17]. The bare metal switches are Pica8 3290, running PicOS 2.6.32 as Operating System (OS) and Open vSwitch v2.3.0 as switching software. As for the software based devices we use servers with one onboard Intel I217-LM and an 4 Port Intel I350 Ethernet Network Interface Card (NIC). The OS is Ubuntu Server 14.04.3 64Bit (3.13.0-32-generic Kernel) with Open vSwitch v2.4.0. On the data network, we employ a total of 6 servers for hosting the agents and generating traffic. Control traffic of the SDN network is handled out-of-band, using a dedicated Zyxel GS1900-24E switch for connecting to the SDN controller. The SDN controller itself runs Ubuntu 14.04.03 (4.0.0 Kernel with low-latency patch). It is forked from the open source, Java based Floodlight controller [18] (OpenFlow v1.3), which we subsequently enhanced and modified to match the specific requirements of Smart Grid communication. Further details on the measurement set-up can be found in [19].

IV. CONCEPT OF MAS-SDN-INTEGRATION

In this section we detail the coupling power grid simulation, MAS and software-defined communication network for achieving reliable grid control, as illustrated in Figure 3.

A. *MAS-based Decentralized Power Grid Control*

The main objective of the MAS is the coordinated activation of available countermeasures for blackout prevention when the power system is close to voltage collapse or threatened by line overloads. As a main feature, the distributed agents do not need complete system information as they rely on local measurements and inter-agent communications. The general idea is the installation of intelligent agents at each node in the transmission system with each agent having a limited observability area, as shown in Figure 2. An agent is only able to communicate with other agents within its observability

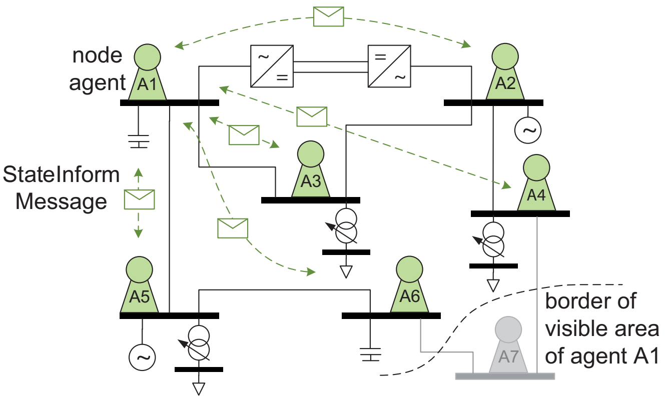

Figure 2: Overview of the MAS for coordinated voltage and power flow control

area, sending and receiving so called *StateInformMessages* that contain information of sender and receiver as well as local measurements, e.g. bus voltages and line loadings. Based on the incoming *StateInformMessages* every node agent performs a distributed topology analysis yielding an estimate of the surrounding network model as well as getting aware of the current system state. For reliable control, it is critical that the node agent continuously updates its topological and system state information. According to the assets connected to an agent's node - in particular power flow controllers, HVDC converters, shunt compensation, or underlying distribution grids - the agent is able to perform the related control actions. For instance, the distributed agents are able to change set points of HVDC-converters or power flow controllers, such as phase shifting transformers or flexible AC transmission system devices, as well as execute a coordinated redispatch of flexible generation and load in order to reduce the power flow on a transmission line [3], [8]. Moreover, the agents can act on load tap changers of transformers between transmission and distribution grid, enable the provision of reactive power by shunt capacitors or flexible distribution systems or, as a last measure, curtail load when the system is already close to voltage collapse [20]. Thus, transmission system voltages can be stabilized by coordinated activation of the available control opportunities. Main features of this approach are its adaptivity to unforeseen network conditions (e.g. (N-k)-cases), its real-time capability and its automated deployment of the controllability of future Smart Grids. By this, storages, demand side management and distributed generation in the distribution grid can support operational security of the transmission network in alert or emergency network conditions.

B. *ICT infrastructure using SDN*

Tailored to the specific demands of Smart Grid communications, our SDN controller provides additional fault-tolerance and QoS mechanisms, enhancing the work of [21]. Using a hybrid failover approach, combining local and centralised methods of failure detection and recovery, we achieve recovery from communication link failures within a few milliseconds, while maintaining route optimality nearly continuously.

QoS guarantees are realised on basis of a fine grained prioritisation technique with priorities from 0 (lowest) to 100 (highest). For this purpose we apply so-called *FlowRequirements* to each traffic flow, which are 4-tuples of maximum latency, maximum packet loss, minimum data rate and priority. Default parameter sets are provided for typical Smart Grid applications such as IEC 61850 services. These parameters are considered for routing traffic flows, whereat the weight of each parameter depends on the routing policy selected. Thus, optimal paths are chosen either with respect to minimum delay, optimal link utilization, load balancing or a combination of these criteria. Particularly, flow priority determines the order, in which traffic flows are handled. Flows with lower priority may be re-routed to sub-optimal paths in order to free resources for high priority traffic. In contrast to our previous work in [21], we employ queuing to realize continuous QoS guarantees, while achieving full link utilization. Therefore, our controller platform has been extended to allow for remote configuration of Open vSwitch queues. Open vSwitch then translates these queues to Hierarchical Token Bucket (HTB) queues, used by the Linux kernel, which - besides the actual priority - provide configurable minimum and maximum data rates. At the controller side, every FlowRequirement is associated with a queue on basis of its priority parameter. A set of controller-internal standard queues maps to the default FlowRequirements and comprises specific minimum and maximum queue data rates. During flow installation these controller-internal queues are translated to actual switch queues by the controller.

C. *MAS messaging*

JADE provides Hypertext Transfer Protocol (HTTP) and Internet Inter-ORB Protocol (IIOP) as FIPA compliant Message Transport Protocol (MTP) options, the former of which we apply for communication between different MAS platforms. For interaction between containers of a platform however, JADE uses Java Remote Method Invocation (RMI) messages instead of the actual MTP, even if containers are placed on different physical hosts. We therefore modify the JADE core to enforce MTP-based intra-platform communication.

To achieve prioritisation of MAS messages within the communication network, switches as well as the SDN controller must be able to identify these message unambiguously. Technically, this would require dissecting packets up to the application layer of the ISO/OSI reference stack in order to discern MAS messages from other HTTP packets and to distinguish the different types of MAS messages. Yet, as for now, OpenFlow matches are limited to a couple of match fields, e.g. Ethernet and IP source/destination or TCP/UDP ports. Matching stops at the transport layer of the ISO/OSI reference stack. Theoretically, extending the number of supported match fields would be possible, however this would increase the processing overhead for matching at the switches as well. Therefore, we present an alternative solution by establishing multiple MTP receiver ports per agent (container) and associating each MAS message type with a dedicated TCP port. Accordingly, during message generation, we ensure that messages are explicitly addressed to their associated receiver port. In this way, switches and SDN controller are enabled to match and prioritise MAS messages appropriately, while adhering to the OpenFlow protocol capabilities.

D. *Integration of MAS and SDN-Controller*

For interaction between the MAS and the SDN controller, we implement the SDN controller's *NBI*, using the RESTful API (Representational State Transfer Application Programming Interface). Here, the controller acts as REST server, providing services via dedicated Uniform Resource Locators (URL). The REST client is integrated into the MAS in such a manner that requests to the SDN controller may be issued either by the master agent or by each agent individually. Yet, for the latter case, an additional physical network interface is required at each agent for connecting to the control network. Our SDN controller is designed to offer three different services - Rule Creation, Resource Reservation and Flow Modification - and their respective revocation - using POST and DELETE requests to dedicated URLs, including application specific information as JavaScript Object Notation (JSON) objects.

1) Rule Creation: Initially, the MAS application and its QoS requirements are unknown to the SDN controller. Therefore, Rule Creation REST requests enable the MAS to transmit its traffic flow specific QoS demands regarding priority, minimum data rate, maximum latency and packet loss (i.e. FlowRequirements) along with a specific packet header pattern (i.e. match) to the controller. Traffic flows are identified by OFMatches, applying dedicated TCP ports as described previously. Thus, the controller is able to handle incoming messages from the MAS, which traverse the standard OpenFlow processing pipeline, as well as select appropriate routes and queues with respect to the signalled requirements.

2) Resource Reservation: As an alternative to the standard OpenFlow processing pipeline, resource reservation allows the MAS to request route set-up previous to transmission. Accordingly, the SDN controller selects a suitable route on basis of the match provided as JSON object within the request and pushes static flow table entries to the switches. Thus, when a registered traffic flow arrives, it is forwarded directly without querying the controller for routing. It has to be noted that the MAS is responsible for triggering the deletion of static flows.

3) Flow Modification: In case of emergencies in the transmission grid (e.g. overload, voltage instability) or altered QoS requirements, the MAS may ask the SDN controller to adapt QoS provisions for a traffic flow, identified by its match. As a consequence, switching of queues or even re-routing of entire flows is triggered. For example, when the power system detects an overload, the MAS requests a temporary raise of priority for traffic flows, which are required for resolving this situation.

V. SCENARIO DESCRIPTION

Figure 3 illustrates the complete system of transmission power grid, MAS and communication network from an ICT point of view. The power system consists of six substations, four of which host agents for grid control. Local measurement data, gained in the power simulation, is provided to the agents by the master agent via a dedicated network (dash-dotted orange lines). Additionally, the SDN controller is connected to this network, enabling agents to disclose their specific communication demands. Apart from that, the SDN controller uses separate control links (dashed green lines) for configuring the switches of the data network. The data network (blue lines) connects the hosts, located in different substations, and serves for transmitting power system traffic, e.g. measurement data or control commands. Besides MAS traffic, we consider IEC 61860 communication services.

Originally, IEC 61850 was developed as a standard for substation automation, comprising complete data models as well as dedicated communication services [22]. In recent years, IEC 61850 has been extended to cover the integration of DER and EV as well as wide area communication, thus evolving to a global standard for Smart Grid communication. Here, we consider TCP-based Manufacturing Messaging Specification (MMS) traffic from host 3 to host 4, commonly used for reports, system configuration and updates. Host 2 and 5 exchange measurement data, using Sampled Value (SV) messaging, which encapsulates information into Ethernet frames directly. Finally, MAS *StateInformMessages* are exchanged between the agents, situated at host 1 and 4. On a default basis, the SDN controller ranks SV messages at a priority of 60, while MMS and MAS traffic receive priorities of 40 respectively 30, with higher values indicating superior QoS. The set-up is completed by a measurement computer, which captures traffic of the data network at hosts 1 and 5, and thus calculates the overall transmission delay (dotted grey lines).

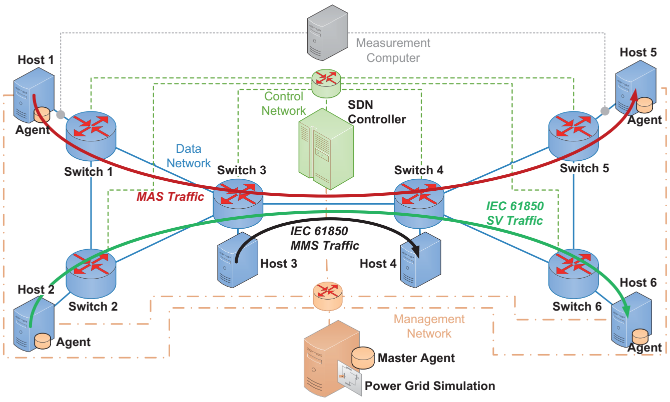

Figure 3: Interaction and Interfaces of SDN-based ICT, MAS and Power Grid Simulation

VI. EVALUATION RESULTS

Our evaluation follows the application of the different services, provided by the *NBI*, and their results.

1) Rule Creation: Requesting the set-up of traffic flow specific QoS demands at the SDN controller is a critical prerequisite to all other use cases. It is required for establishing

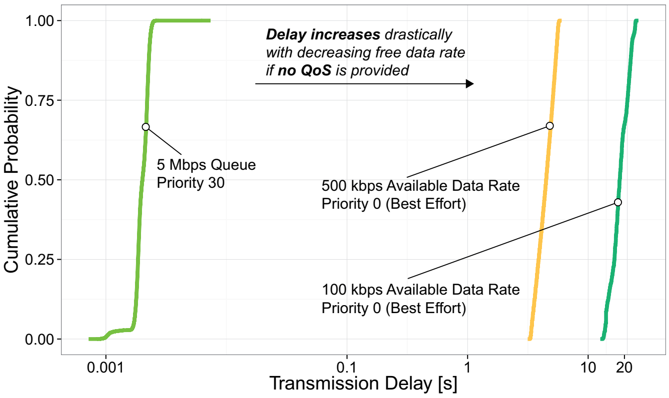

Figure 4: Transmission Delays of MAS Messages with Rule Creation Request (Dedicated Queue) and without (Best Effort)

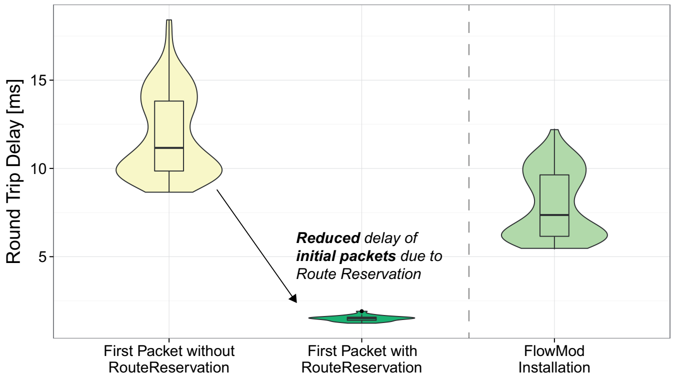

Figure 5: Comparison of RTT for the First Packet of a Traffic Flow with and without Route Reservation Request

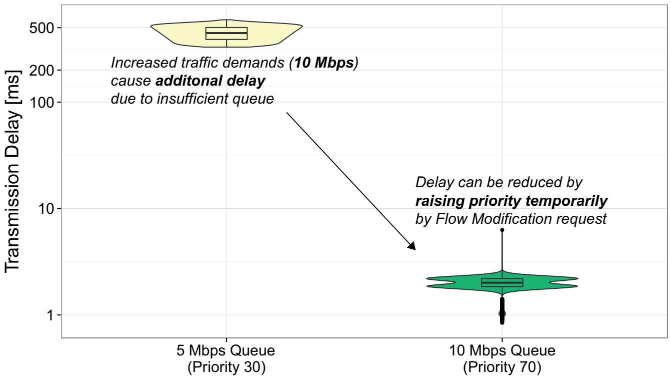

Figure 6: Transmission Delay of MAS Traffic with Increased Capacity Demand in Standard Queue and High Priority Queue

fine-grained prioritisation between data streams. Figure 4 shows the cumulative distribution functions (logarithmic scale) for transmission delays of MAS *StateInformMessages* with and without Rule Creation request. As outlined previously, we assume parallel transmissions of SV and MMS messages, evoking a bottleneck on the link between Switch 3 and 4 (cf. Figure 3). In case a *NB* request is issued prior to data transmission, MAS traffic is identified and assigned to a $5\,\mathrm{Mbps}$ minimum rate queue with priority 30, following our default FlowRequirements and queue pattern. Thus, *StateInformMessages* can be exchanged without interference, experiencing a mean delay of $2.01\,\mathrm{ms}$ (maximum delay: $6.29\,\mathrm{ms}$). In contrast, if no REST request is sent, MAS traffic is treated on a best effort basis without data rate guarantees. In the worst case, on a fully utilized link, best effort traffic is suppressed completely with transmission delays converging to infinity. To illustrate this, we decreased the available data rate for MAS messages gradually to $500\,\mathrm{kbps}$ and then $100\,\mathrm{kbps}$, causing a drastic increase in latency with mean values of $4.49\,\mathrm{s}$ and $18.61\,\mathrm{s}$.

2) Resource Reservation: Figure 5 visualizes massive performance improvements, which are achieved by route reservation via the *NBI*. The Round Trip Time (RTT) of the first packet of the data exchange between agents at hosts 1 and 5 is measured at the sender side. It is illustrated with the help of violin plots and overlaid box plots, showing range, median and frequency of the results. In case the route has been established previous to traffic transmission, the traffic flow's first packet experiences the same RTT as all subsequent packets, with a median of $1.52\,\mathrm{ms}$, assuming no interfering traffic. In comparison, if the first packet is handled by the standard OpenFlow processing pipeline the RTT has a median of $11.16\,\mathrm{ms}$ and a maximum of $18.42\,\mathrm{ms}$. In addition, the violin on the right hand side shows the delay of OpenFlow FlowMod installation. This corresponds to the interval between transmitting an OFPacketIn message to the controller and the reception of the associated OFFlowMod message at the switches on the traffic flow's path. Thus, two-way delay between switch and controller as well as controller processing times are captured, whereas processing at the switches is excluded. The median installation delay amounts to $7.36\,\mathrm{ms}$, which constitutes a major part of the first packet's overall RTT, assuming the traffic flow was not set up previously.

3) Flow Modification: In order to dynamically adapt to changing communication requirements of the MAS, agents can send Flow Modification requests to the *NBI* of the SDN controller. Subsequently, priority and queue configurations of the affected traffic flow are altered. Here, we take up the scenario, established in Section V, including the bottleneck situation on the link between Switches 3 and 4, considered in the Rule Creation use case. Moreover, MAS traffic has been classified as priority 30 and directed to a corresponding $5\,\mathrm{Mbps}$ minimum rate queue already.
Yet, in case of an emergency situation in the power system, agents need to trigger remedial actions to reduce power flows on overloaded transmission lines and preclude voltage collapse, causing additional traffic load on the communication links. Without applying Flow Modification requests, critical agent communication receives the guaranteed capacity of $5\,\mathrm{Mbps}$ only, which - on the overloaded communication link - falls short of the increased data rate requirement. Thus, higher ranked SV and MMS traffic block the additional MAS messages, causing risen delays of up to $593.72\,\mathrm{ms}$ (median $445.21\,\mathrm{ms}$) as shown by the left violin in Figure 6 (logarithmic scaling). In contrast, delay can be kept to normal levels with a median of $2.01\,\mathrm{ms}$ (right violin), if MAS traffic is switched to a higher priority queue, translating a corresponding REST request. Accordingly, time limits for remedial actions in the power grid, e.g. for voltage control, are and collapses avoided. In addition, Figure 7 illustrates the process of applying altered priority / queue configurations, captured at Switch 3, to the communication network, following the Flow Modification request to grant extra capacity for MAS messages. At about $3.15\,\mathrm{s}$ the available data rate for MAS traffic - on the congested link between Switches 3 and 4 - is raised, entailing decreasing data rates of now lower ranked MMS communication.

VII. CONCLUSION

In this paper, the interconnection of future power system control and communication networks is illustrated, demon-

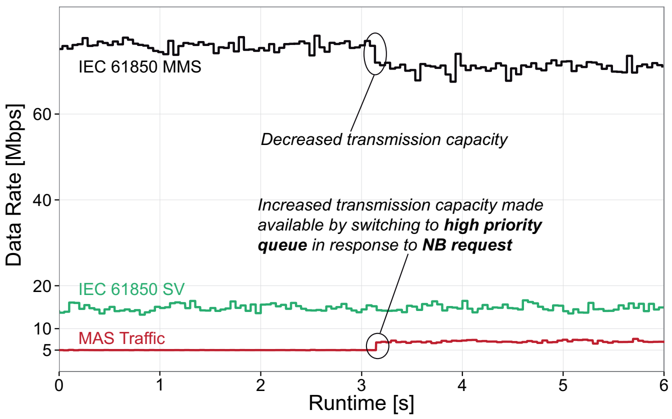

Figure 7: Data Rates of MAS, MMS and SV Messages on Congested Link at Switch 3

strating how close linkage of MAS and SDN-driven ICT infrastructure ensures reliable, timely transmission of critical grid control messages. Our concept establishes communication between agents and the SDN controller via the Northbound Interface. Thus, agents are enabled to indicate their varying traffic demands to the SDN controller, which translates these requirements to priorities and provides appropriate queues at the switches within the communication network. We show that announcing communication requirements is indispensable for QoS guarantees, especially if bottlenecks of the ICT infrastructure need to be traversed. Also, route reservation reduces delay by 86 % during flow set-up. Flow Modification requests are applied for adapting priority and queue configuration to altered capacity demands of the MAS. Thus, risen delays in the range of hundreds of milliseconds on congested links are prevented, enabling timely actions of control agents to avoid overloads or voltage collapse.

In future work, we will analyse in detail the influence of further QoS parameters, e.g. latency or packet loss. To avoid extra connection of the SDN controller to the MAS management network for transmitting requests, a dedicated channel for in-band host-controller communication will be established. From a power system perspective, elaborating on the consequences of insufficient communication capacities on transmission grid stability will be a major objective of research. Moreover, we aim at determining an optimal visibility area for agents of the MAS by finding an ideal trade-off between best information quality for grid control and minimal communication effort.

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