Network Slicing for Critical Communications in Shared 5G Infrastructures - An Empirical Evaluation

Fabian Kurtz, Caner Bektas, Nils Dorsch, Christian Wietfeld
Communication Networks Institute, TU Dortmund University, Otto-Hahn-Strasse 6, 44227 Dortmund
Email: {fabian.kurtz, caner.bektas, nils.dorsch, christian.wietfeld}@tu-dortmund.de

Abstract—Increasing automation in systems such as Smart Grids (SGs), Intelligent Transportation, the Internet of Things (IoT) and Industry 4.0, involves the need for robust, highly capable Information and Communication Technology (ICT). Traditionally, to meet diverging use case requirements regarding network data rate, delay, security, reliability and flexibility, dedicated communication infrastructures are employed. Yet, this is associated with high costs and lengthy roll-out times. Therefore it is desirable for multiple tenants to share one Physical Network (PN). However, this may compromise service guarantees, potentially violating Service Level Agreements (SLAs). Network slicing aims to address this challenge by transparently dividing one common infrastructure into multiple, logically independent networks. Thereby tenants are isolated from one another, ensuring the fulfillment of hard performance guarantees. As slicing is central to realizing the potential of 5G networks, this work presents a novel approach based on Network Function Virtualization (NFV) and Software-Defined Networking (SDN) driven queueing strategies. The developed solution is comprehensively evaluated with realistic traffic in a physical testing environment. Highly demanding critical infrastructure use cases, with multiple service levels per slice, are used to validate performance and demonstrate functionalities such as dynamic data rate allocation.

I. INTRODUCTION

Developments such as the emergence of Smart Grids, largely driven by a shift to renewable energy resources, Intelligent Transportation Systems (ITSs) with self-driving cars and the IoT place increasing demands on ICT. Traditionally, such Critical Infrastructures (CIs) require dedicated communication networks to meet their specific, diverging requirements [1]. However, this methodology incurs high costs and communication resources can not easily be deployed and scaled according to demand. Hence, 5G proposes to instantiate multiple, virtual networks, so called network slices, on top of one underlying, shared (public) Physical Network (PN) [2]. This approach aims to provide independent networks, meeting the requirements of individual use cases, while reducing costs and configuration overhead. For slicing in 5G architectures the three main categories Enhanced Mobile Broadband (eMBB), Massive Machine Type Communication (mMTC) and Ultra-Reliable Low Latency Communication (uRLLC) have been defined, as shown in Figure 1 [3][4]. Due to their relevance for CI, the latter two are the main focus of this paper, while eMBB is used to generate bulk traffic. Although network slicing is crucial to fulfill the performance targets of 5G, currently no standard has been selected. Therefore, this work introduces a novel solution for CI communications in shared 5G infrastructures. By building on SDN and the European Telecommunications Standards Institute (ETSI) NFV architecture, we demonstrate the ability to provide hard service guarantees. A dedicated SDN controller for Management and Orchestration (MANO) provides individual slices, each in turn managed by its own controller. This strategy not only facilitates multiple tenants to share the same PN, but also enables new business models. Hence, clients such as SG Distribution System Operators (DSOs) can either configure network resources by themselves or utilize a fully managed slice via SDN’s northbound Application Programming Interface (API). As slices are isolated from one another, overloads, e.g. caused by Distributed Denial of Service (DDoS) attacks or misconfiguration, are shown to have no impact on other slices. Also, flexible data rate allocation is demonstrated, allowing excess network capacity to be utilized by other traffic flows according to their priority. Beyond a scalability and performance evaluation, we validate our approach empirically by way of a real-world application scenario based on ITS Floating Car Data (FCD) [5] and IEC 61850 [6] 5G traffic requirements. This paper is structured as follows: Section II provides an overview of related work. Next, Section III details three key aspects of this publication. First the general concept of 5G network slicing architectures is described. Subsequently, requirements of critical infrastructure communications are presented. Lastly, our NFV and SDN driven network slicing concept is detailed. Section IV introduces the employed testing methodology and evaluation scenarios. Afterwards, Section V discusses results, highlighting performance and scalability observations.

Figure 1: Overview of a Sliced 5G Communication Network
II. RELATED WORK

Related work presented in the surveys of [2], [7], [8], [9] and [10] emphasizes the importance of SDN and NFV for network slicing. Also general challenges and possible solutions are identified, yielding comprehensive overviews of the topic. Theoretical works meanwhile mostly focus on specific aspects of slicing, such as [11] who also identify NFV as key enabling technology. Approaches for slice selection and routing between Virtual Network Functions (VNFs) are developed in [12]. The interplay of cascading SDN controllers in sliced architectures is the focus of [13]. Algorithms, for example regarding optimized allocation of available network resources, are studied in [14], [15] and [16]. In contrast, we focus on an empirical evaluation of physical communication links resource sharing, as required by slicing. Works which implement slicing technologies, often employ or extend FlowVisor [17], a transparent proxy between OpenFlow (OF) switches and multiple SDN controllers. Among these studies [18] and [19] concentrate on slice management, respectively security aspects. An extension of FlowVisor with a general Quality of Service (QoS) scheme based on flow redirection is presented in [20]. Other solutions constitute a more flexible and universal basis for slicing, by building on SDN and NFV. Yet, Virtual LANs (VLANs) are mostly used as a means for traffic separation, a concept similar to FlowVisor. Management functionalities such as slice (de-) provisioning are discussed in [21], [22] and [23] provide further works in this area, using an OpenDaylight controller [24]. An analysis of fast slice failover strategies is given in [25], while [26] describes challenges and solutions of Radio Access Network (RAN) slicing via LTE [27] and IEEE 802.11 [28] air interfaces. However, contrary to this paper, these works don’t harness the potential of SDN and NFV fully, thus increasing system complexity and overhead. In summary, no work fully addresses the challenges of allocating available physical communication resources to virtual network slices in an efficient and dynamic manner. Hence, this paper not only develops a technical solution to network slicing suitable for deployment in current SDN and NFV enabled communication infrastructures, but also verifies the approach by a thorough, empirical performance evaluation.

III. SOFTWARE-DEFINED NETWORKING AND NETWORK FUNCTION VIRTUALIZATION BASED 5G SLICING

This section first introduces the concept, requirements and architectural framework of 5G network slicing. Next, the challenges of CI communications, particularly in shared infrastructures, are discussed. Afterwards we present our approach to slicing and illustrate its implementation.

A. 5G Network Slicing - Architecture and Concept

As illustrated by Figure 1, the next generation of mobile communication (5G) proposes the virtualization network resources. Through this multiple isolated network partitions, called slices, are created. This facilitates the deployment of use cases with differing demands on the same physical communication infrastructure. In this context, 5G distinguishes three main categories. eMBB is aimed at data rate intensive services (up to 20Gbps) such as ultra high resolution video, fixed wireless broadband or Augmented (AR) and Virtual Reality (VR). With the emergence of IoT devices and Industry 4.0, inter-machine communication increases significantly. Although per user user rates are low, a massive number of devices physically distributed over large areas poses its own challenges. An example of this is Smart Metering in SGs, i.e. the automated collection of energy generation and demand down to customer or even device level. Hence, such mMTC use cases require a dedicated network (slice) to meet their performance targets. The third major scenario included in 5G addresses mission critical, latency sensitive applications, termed uRLLC services. An example are ITSs with FCD based vehicle-to-X communication. End-to-end delays below 1ms have to be guaranteed at all times, enabling fast control loops and thus reactions. Protection mechanisms for electric power transmission in SGs, as outlined in the next section, constitute another example of uRLLC. To meet these diverging requirements networks need to support slicing. Therefore NFV and SDN are widely considered key components of upcoming 5G infrastructures [2]. Figure 2 presents the generic NFV architecture defined by ETSI, extended with modules of our approach to network slicing. Leveraging these technologies, we illustrate our slicing concept in the following sections.

B. Requirements of Critical Infrastructure Communications

Modern critical infrastructures increasingly rely on ICT to reliably fulfill their requirements. However, dedicated networks are frequently required to provide the necessary level of performance, traffic isolation and manageability. Hence, network slicing is an ideal solution to these challenges. To be viable, the demands of CI communications in terms of data rate, latency, reliability and more have to be met. In this regard ITSs are a prominent field of application. Driven by the shift to increasing levels of driving automation, incrementally more FCD traffic is generated. FCD contains for instance information about vehicle location, direction of travel, speed and other status data. By exchanging these messages between vehicles or transmitting it via e.g. cellular networks to cloud infrastructures for analysis, road traffic can be optimized and
accidents reduced. As no general industry standard specifying
packet size and Inter-Transmission Time (ITT) exists, we
utilize values from literature [5]. Assuming a scenario in which
vehicles travel on a highway at \(130\frac{km}{h}\) a 5G uRLLC com-
pliant end-to-end delay of \(1ms\) equals a traveled distance of
\(\sim 3.6cm\). Conversely, passenger internet access for business or
entertainment purposes, as an example for eMBB applications,
is not as latency but more data rate sensitive than FCD.
Another especially challenging CI are SGs. The increasing
share of renewable energies calls for powerful monitoring
and control solutions. Therefore, stable operation necessitates
pervasive, robust communication infrastructures. Electric util-
ities such as Transmission System Operators (TSOs) need
to protect their high-voltage power lines and substations
against faults, relying on Wide Area Monitoring Protection
and Control (WAMPAC) and Supervisory Control and Data
Acquisition (SCADA) systems. For this purpose inter-
and intra-substation communication utilizes the IEC 61850 [6]
protocol as developed by the International Electrotechnical
Commission (IEC). The standard defines three main mes-
sages types aimed at different tasks. Manufacturing Message
Specification (MMS) is employed to configure electrical grid
devices. In contrast, Sampled Values (SV) and Generic Object
Oriented Substation Events (GOOSE) are used for transmit-
ting measurements, respectively events. Both are encapsulated
in transmission protocols is available. A mMTC network slice is suitable
for this application, as data rates and ITTs are comparatively
low, while millions of devices can be deployed.

C. An NFV and SDN driven Approach to Network Slicing

Our approach to network slicing builds on NFV and SDN,
to meet 5G’s functionality and performance targets. Traditio-
nal communication infrastructures integrate services such as
load balancing, firewalls and intrusion detection in custom
hardware appliances. In contrast, NFV decouples hard-
and software, abstracting functionalities into VNFs running on
Commercial Off-The-Shelf (COTS) server platforms, e.g. in
clouds. Thus mass-produced computing, storage and switching
components can be used to flexibly deploy, scale and chain
network services as needed by 5G communication. SDN is
closely related to the concept of NFV. Typically decentralized
devices such as routers handle packet switching as well as
network control. In SDN dedicated Data Plane (DP) devices,
i.e. switches without any routing capability, perform physical
data forwarding. Hence, routing is centralized on the Control
Plane (CP) via a so-called SDN controller. Thereby, control
decisions are based on a global instead of local network
states, while CP and DP can be upgraded independently.

Thus, performance as well as efficiency are increased, and
the network can be configured centrally and flexibly, meeting
the requirements of dynamic use cases such as CIIs. The DP is
configured via the southbound API, mostly by way of the de
facto standard OF protocol [30]. Multiple controllers are linked
through the east-, respectively westbound APIs, enabling
scalability. Applications interface with the SDN controller over
the northbound API, re-configuring communication according to
service requirements. For both APIs no pervasive standard
is currently available. SDN and NFV are complementary
approaches, as the controller can dynamically route traffic
flows between VNFs, while being deployed as VNF itself.
While many approaches to slicing build on VLANs for sharing
physical communication resources, we build on queueing
strategies (in this case Hierarchical Token Bucket (HTB)) in
combination with SDN and NFV, as depicted by Figure 2.
Open vSwitch (OVS) [31], an open-source virtual multilayer
switch, is deployed on all bare-metal or virtualized DP devices
of the network. On this basis our SDN-MANO controller
creates a main bridge in each switch, which includes the
respective physical ports. Next, one bridge per slice is added or
removed as needed, as shown by Figure 3. These slice bridges
contain virtual ports, which are nested within the main bridge.
The MANO controller serves as an orchestrator, dynamically
instantiating slice controllers (e.g. via Docker [32]), which can
potentially be optimized for individual use cases. When traffic
enters the DP, i.e. the main bridge, our MANO controller
assigns packets, e.g. via their protocol or other criteria sup-
ported by OF, to the respective slice bridge. There the slice’s
controller routes packets to their virtual destination port, where
the flow is mapped to the main bridge’s proper QoS queue
and physical port. These actions are repeated on each hop to
the destination. Flows which match no slice are classified as
best effort traffic. Although Ethernet is used in combination
with queues to share the PN’s available data rate, the presented
approach can be adapted to other technologies. While we focus
on wired 5G communication, provisions are made to ensure
compatibility with air interface slicing technologies.

![Figure 3: The Developed Network Slicing Architecture](image-url)
IV. TESTING ENVIRONMENT AND EVALUATION SCENARIOS

This section provides a detailed description of the varied scenarios under study and the corresponding testing setup.

A. Testing Environment

The testing setup consists of 13 identical servers, each equipped with an Intel Xeon D-1518 Central Processing Unit (CPU) (four cores at 2.2GHz), 16GB of RAM and six 1GBase-T Ethernet ports from two Network Interface Cards (NICs) (four: Intel I350, two: Intel I210). All devices utilize Ubuntu Server 16.04.3 LTS (v4.13.0-32-generic x86-64 Kernel) as Operating System (OS). Three computers are deployed as virtual switches by running Open vSwitch version 2.5.2, and thus constitute the sliced data-plane evaluated in this paper. As can be seen from Figure 4, six servers are assigned in pairs to the three use cases studied in this work and set up as hosts to either send or receive traffic over the sliced network. Another four machines act as SDN controllers, three of which employ Floodlight (v1.2) [33], managing the Smart Grid, Intelligent Transport and Best Effort Slices. The remaining device runs Ryu (v4.19) [34] and acts as SDN-MANO controller, creating slices for orchestration by the other controllers. To avoid any interference of measurements on the solution under study, three distinct networks are used: out-of-band control, maintenance and the sliced data-plane. Maintenance (not depicted in Figure 4) and control communication are each handled via a Zyxel GS1900-24E switch. The Precision Time Protocol (PTP) in Figure 4) and control communication are each handled via a Zyxel GS1900-24E switch. The Precision Time Protocol (PTP) [35] is employed to synchronize all devices within the testing setup, yielding a mean clock deviation of 16µs and 152µs at maximum. With the exception of the real-world application scenario given in IV-B3, User Datagram Protocol (UDP) traffic loads are created with iPerf2 community edition (v2.0.10) [36]. For assessing our solution’s overhead, we determine the maximum performance of the testing setup without slicing. Ethernet framesize at OSI model layer 2 is 1512Byte (from here on referred to as layer 2 data rate). We use this as a point of reference, as our solution is embedded on this level. Performance evaluations (Section IV-B1) operate on layer 4, resulting in a payload (i.e. goodput) of 1470Byte. Thus, the maximum usable layer 4 data rate is 97.2% of the layer 2 data rate, i.e. 97.2Mbps goodput on a 100Mbps queue. Measurements are repeated at least 100 times with a minimum duration of 1 min per run. Dependent on payload size and ITT, latencies without slicing range from 0.25ms to 1ms.

B. Evaluation Scenarios

The scenarios on which the evaluation of the developed network slicing solution is based are as follows:

1) Scenario A - Performance Study: For evaluating the performance of our end-to-end slicing solution, we focus on several key aspects resulting from 5G and CI communication requirements. Therefore, delay and data rate for varying degrees of network load are studied. On this basis we determine the overhead of our approach, to highlight the efficient use of available resources. This is facilitated by the use of 100Mbps Ethernet, which avoids any possible limitations of the evaluation setup interfering with the general concept, while also affording us the option to closely monitor CPU load during testing. Furthermore the isolation, i.e. independence of different slices is verified. This is particularly important to preclude any detrimental effects of errors or overloads in one virtual infrastructure on other tenants sharing the same PN. Hence, slice utilization is stepwise increased beyond the limit of 97.2% layer 4 goodput. This effectively represents a case in which a tenant transmits with a higher data rate, e.g. due to a DDoS attack, than allocated (i.e. rented or bought slice capacity). Misconfiguration by the PN operator is studied as well. Here two slices, with their combined maximum data rate exceeding the PN’s capabilities, are used simultaneously.

2) Scenario B - Scalability Analysis: To represent an approach viable for deployment in large-scale, multi-tenant communication infrastructures, we demonstrate our solution’s scalability in the following. Ideally end-to-end delays should not be influenced by the number of concurrent slices and their traffic load. Accordingly we analyze delay performance for no, 2, 8 and 16 slices. Available data rate is shared equally among all virtual networks, with traffic streams configured to utilize 100% slice capacity. Thereby any increase in delay can be attributed to side-effects of our solution, instead of overloads caused by congestion. Moreover, we validate slice isolation and end-to-end delay stability. This is achieved by subjecting seven out of 21 slices to UDP based traffic with data rates above the allocated limit. Contrary to scenario A, 1Gbps Ethernet is used to stress test concept and testing setup.

3) Scenario C - Critical Infrastructure Communication: Based on the challenging requirements of CI communications, we devise a testing scenario including real-world traffic flows such as FCD of ITSs and the IEC 61850 SG protocol. Both use cases are equally important and hence are allocated slices of the same priority, including dedicated SDN controllers. SG protection and FCD are classified as uRLLC 5G services and are assigned the highest priority in their corresponding slices. To demonstrate our solution’s ability to discern different traffic
Table I: Slices and Traffic Flows of the CI Comm. Scenario

<table>
<thead>
<tr>
<th>Slice (Descending Priority)</th>
<th>Use Case</th>
<th>5G Service Class</th>
<th>Priority within Slice</th>
<th>Hard Min. Data Rate [Mbps]</th>
<th>Max. Delay [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smart Grids</td>
<td>Protection (IEC 61850)</td>
<td>uRLLC</td>
<td>Highest</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Smart Metering</td>
<td>mMTC</td>
<td>High</td>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>Intelligent Transportation Systems</td>
<td>Floating Car Data</td>
<td>uRLLC</td>
<td>Highest</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Passenger Internet</td>
<td>eMBB</td>
<td>Low</td>
<td>450</td>
<td>10</td>
</tr>
<tr>
<td>Best Effort</td>
<td>Multimedia</td>
<td>None</td>
<td>Lowest</td>
<td>None</td>
<td>100</td>
</tr>
</tbody>
</table>

Evaluation results of the previously detailed slicing solution, obtained with the aid of our physical testing environment, are presented and discussed in the following sections.

V. EVALUATION RESULTS

A. Delay and Data Rate Performance

Figure 5 shows the end-to-end delays of two slices for varying traffic loads. Slices A and B share a physical 100Mbps Ethernet network fairly and transmit UDP traffic. As discussed in Section IV-A, some data rate is consumed by protocol headers. In effect 97.2% of layer 2 data rate remains as layer 4 goodput, regardless of the chosen approach. Hence, at 96% to 97% Slice A and B have a median end-to-end delay of 1.05ms with an variance of ca. ±0.05ms. However, if a data rate exceeding Slice B’s allocation is forced into the network, an overload is created. While Slice A stays at its assigned limit (97.2% layer 4 goodput normalized to layer 2 data rate), the traffic of Slice B is increased in 1% steps. As indicated in Figure 5, this user-driven overload (e.g. due to a DDoS attack) leads to a sharp rise in delays, with medians up to 1,212ms at 101% load. Crucially the observed delays in Slice A remain unaffected, even compared to no slicing, as shown by the enlarged violin plots. Hence, slice isolation is demonstrated.

Misconfiguration by the PN operator is illustrated by Figure 6. Here, Slice A has an allocated queue data rate (i.e. layer 2 data rate) of 40Mbps, effectively yielding 38.9Mbps on layer 4. The total sum of queue data rates (x-axis) should not exceed the theoretical maximum layer 2 data rate of a 100Mbps Ethernet link. This maximum is the ratio between frame sizes at layers 2 and 1, which yields \( \frac{1512\text{Byte}}{1352\text{Byte}} = 98.7\% \). As Slice B’s available queue data rate increases in 1Mbps steps, the queues’ total sum eventually exceeds the 98.7Mbps limit, representing a misconfiguration. In that case Slice B tries to utilize resources that do not exist. Accordingly the 97.2% layer 4 goodput is no longer obtainable for Slice B, as A consumes the HTB mechanism’s tokens. Hence, Slice A’s data rate remains stable while B can not use its assigned capacity and stagnates at 56.9Mbps, which is below 97.2% of the configured 60Mbps queue data rate. No overhead in terms of achieved throughput is observed, confirming expectations.

![Figure 5: End-to-End Delays of Two Slices for Varying Traffic Loads, Including Overloads in Slice B](image-url)

![Figure 6: Impact Analysis of Misconfiguration by the Physical Communication Network Operator, i.e. Slice Provider](image-url)
B. Scalability of the Proposed Slicing Solution

Figure 7 shows the presented slicing solution’s scalability. End-to-end delays of a dedicated and several sliced networks (1Gbps capacity) is given. Data rate is allocated fairly, with all slices idle but one. Delays remain stable up until sixteen concurrent slices, at which point outliers of up to 0.36ms occur. Investigations reveal this to be a result of CPU context switches, necessitated since the employed hardware provides a maximum of eight threads and queues. Outliers down to 0.17ms are likely caused by the non-realtime OS’s reduced timer/interrupt coalescing, triggered by the raise in computational load. Performance optimizations of the developed source, realtime kernels and higher thread-count CPUs should address this for deployment in highly-sliced networks.

A stress test of scalability is given by Figure 8. In normal operation (left side) 21 coexisting slices fully utilize their allocated data rate, achieving stable end-to-end delays with a median of 1ms. Delays are higher than in the previous case as more slices share a slower PN (100Mbps). During partial overload (right side) seven slices try to exceed their allocated data rate. Accordingly their delays rise to 3.5s, while slices without overloads remain unaffected. Thus network isolation remains robust even under high loads in several slices. Data rate remains stable across all presented scalability tests.

C. Critical Infrastructure Communication Scenario

For the CI communication scenario Figure 9 shows the measured data rate of the traffic flows given by Table I. At first only best effort traffic is present, fully utilizing the PN. This use case continues to transmit with 950Mbps, regardless of available data rate, but has no guaranteed minimum data rate and can thus be displaced by other slices. Hence, once passenger internet, respectively FCD traffic of the ITS slice enters the network, nearly instantaneously best effort throughput reduces accordingly. The same applies when Protection and Smart Metering traffic of the 5G slice are introduced. A simultaneous 50Mbps increase of Protection and FCD traffic at 90s into the measurement, serves as an especially critical test case. Both use cases can see a spontaneous rise in their demands, e.g. due to faults in the electrical grid forcing increased monitoring and control activity. While fast reactions with precise data rate levels are shown, Figure 10 confirms that hard service guarantees are provided during transitions. Here best effort traffic typically stays below the desired 100ms boundary. Yet, outliers to 350ms occur, resulting from slice overloads, i.e. after 10s in Figure 9. Smart Metering and passenger internet delays are below 3ms with ~1.3ms medians, meeting service level guarantees. Outliers result from the starting phase, with stable delays throughout runs. The violins of protection as well
as FCD traffic show a slight delay variance during slice reconfiguration. However, requirements are fulfilled with delays mostly below 0.5ms. Thus a delay budget, which is sufficient for 5G new radio air interfaces, is obtained.

VI. CONCLUSION AND OUTLOOK

In this work we present an NFV and SDN based approach to network slicing for CI communications in shared 5G infrastructures. Building on nested bridges and HTB queueing, an ETSI NFV compatible solution is implemented and thoroughly analyzed. Performance is validated by way of a physical testing setup, showcasing slice isolation even during partial overloads. Scalability is highlighted as well, with no performance reduction aside from cases with highly sliced networks. Here, virtual hops between bridges increase computational loads, yet optimizations are identified for further improvements. A real-world scenario with 5G and ITS traffic flows covering 5G’s service classes is discussed. Dynamic data rate allocation, slice re-configuration and the ability to provide hard service guarantees under realistic conditions with enough headroom for 5G new radio air interfaces are demonstrated. Future work will concentrate on the integration of the here described solution with a mmWave radio interface. Thereby a comprehensive 5G end-to-end slicing architecture will be created, capable of transparently hosting multiple tenants while meeting challenging requirements imposed by e.g. Smart Grids. Furthermore, network orchestration will be studied to achieve policy-based automated deployment, configuration and management of VNFs and slices (as required by individual services). An evaluation in field trials is targeted to provide an in-depth performance validation in realistic CI deployments.

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