The Fog Development Kit: A Development Platform for SDN-based Edge-Fog Systems

Colton Powell, Christopher Desiniotis, and Behnam Dezfooli
Internet of Things Research Lab, Department of Computer Science & Engineering, Santa Clara University, USA
ctpowell@scu.edu, cdesiniotis@scu.edu, bdezfooli@scu.edu

Abstract—With the rise of the Internet of Things (IoT), fog computing has emerged to help traditional cloud computing in meeting scalability demands. Fog computing makes it possible to fulfill real-time requirements of applications by bringing more processing, storage, and control power geographically closer to edge devices. However, since fog computing is a relatively new field, there is no standard platform for research and development in a realistic environment, and this dramatically inhibits innovation and development of applications suitable for the fog. In response to these challenges, we propose the FDK: A Fog Development Kit for software-defined edge-fog systems. By providing high-level interfaces for allocating computing and networking resources, the FDK abstracts the complexities of fog computing from developers and enables rapid development of edge-fog systems. Also, the FDK supports the utilization of virtualized devices to create a highly realistic emulation environment, allowing fog application prototypes to be built with zero additional costs and enabling portability to a physical infrastructure. We evaluate the resource allocation performance of the FDK using a testbed, including eight edge devices, four fog nodes, and five OpenFlow switches. Our evaluations show that the delay of resource allocation and deallocation is less than 279ms and 256ms for 95% of edge-fog transactions, respectively. Besides, we demonstrate that resource allocations are appropriately enforced and guaranteed, even amidst extreme network congestion.

Index Terms—Internet of Things (IoT), Edge Computing, Fog Computing, Software-Defined Networking (SDN), Resource Management

I. INTRODUCTION

In today’s world of smart cars, smart cities, smart homes, Industry 4.0, and mobile healthcare, almost every device is connected to the Internet. Whether they be televisions, sensors, or wearable devices, these technologies often generate data and require computation and storage needs that cannot be met at the network edge. With the growing number of interconnected devices and IoT applications arises the challenge of handling a massive amount of data in a highly efficient manner.

Cloud computing offers a partial solution to this dilemma by providing massive infrastructure and powerful applications, which can ultimately be used to meet these needs. However, cloud computing is not suitable for scenarios involving real-time and mission-critical applications with stringent runtime and latency requirements [1]. Additionally, cloud computing cannot scale sufficiently to handle the processing, storage, and communication demands of billions of IoT devices. Fog computing aims to solve this challenge by bringing additional computing, storage, and control capabilities closer to the network edge. The increased number of powerful computation and networking platforms has made the immediate implementation of fog architectures a worthwhile undertaking [2]. Fog is intended to work alongside the cloud, forming an edge-fog-cloud continuum where applications can be served promptly depending on their requirements [3].

By using the edge-fog-cloud continuum, IoT requests can be serviced in the fog, thereby avoiding transmission to the cloud and significantly reducing packet latency and congestion within data centers. Resource-constrained devices, such as tiny sensors and smart medical devices, can offload computationally-intensive tasks to nearby fog nodes to meet real-time constraints. For example, consider a scenario where medical edge devices in a hospital can request processing resources of fog nodes. Once an edge device detects an anomaly, it can request powerful resources from fog nodes for further processing and real-time results. We refer to these systems as edge-fog systems, where applications on edge devices may offload some computation to nearby fog nodes. These systems may optionally connect to cloud data centers for increased accuracy in the decision-making process.

Unfortunately, there exist significant obstacles for research and development in the realm of edge-fog systems. First, edge devices need to request and reserve resources to meet the Quality of Service (QoS) demands of underlying applications, meaning that any efficient edge-fog system must operate with a resource allocator. Traditional load balancers are not sufficient to fulfill the needs of heterogeneous IoT applications, where devices at the edge of the network require guaranteed resources to meet their stringent runtime and latency requirements. While many resource allocation platforms have been proposed [4]–[6], few systems allocate both networking and computing resources. Furthermore, to the best of our knowledge, no such platforms have integrated software-defined networking (SDN) into their architecture, where fog node resource allocation, network bandwidth allocation, and customizable routing policies are all consolidated into a single, comprehensive edge-fog platform. Second, most of the existing works employ simulation to evaluate the efficiency of their resource management approaches [5]–[10], and this highlights an apparent lack of development tools for research in this field. In order to exhaustively test new approaches in realistic environments, and to accelerate research in fog computing, a standard research and development platform is needed. Finally, it can be quite expensive to prototype and test the performance of a real edge-fog application. For example,
creating even the most straightforward edge-fog application requires constructing an infrastructure of edge devices, fog nodes, and networking hardware, which can be costly. Therefore, the development of any edge-fog application must be preceded by the creation of complex software components and a costly physical infrastructure. Clearly, this combination of complexity and cost poses an immense barrier-of-entry for researchers and engineers. Since fog computing is still in its infancy, there is no standard development kit or platform which has solved all of these issues in the form of a single, complete development package. Without such a platform, the advancement of pertinent, real-time edge-fog applications will be slow, given the barriers-of-entry present in the realm of edge-fog systems.

In this paper, we set out to address this problem by proposing the Fog Development Kit (FDK): A fog computing development platform for software-defined edge-fog networks. The FDK is intended to bring together all of the elements of edge-fog computing into one comprehensive package, where developers can begin building edge-fog systems with ease and without all of the aforementioned barriers.

The FDK addresses the complexity of developing edge-fog systems by providing a cutting-edge resource allocation scheme, which supports any arbitrary edge-fog application running on top of it. Specifically, by integrating SDN and virtualization technologies, the FDK enables edge devices to utilize its messaging protocol and request computing and communication resources. If sufficient resources are available, the FDK instantiates a container in the fog with the desired computing resources, finds a path in the network for edge-fog communication, and allocates the requested bandwidth along the identified path. All of the resource allocation complexity is thus taken care of by the FDK. For example, suppose a developer plans to build a facial recognition system, where resource-constrained edge devices connected to cameras live-stream video data to the fog for heavy-duty processing. Here, it is only required to develop an edge-side application to collect and stream video data, as well as the containerized fog-side service to receive and process the data. The FDK handles all of the underlying complexities of the system such as managing computational resources of fog nodes, path reservation and bandwidth slicing between edge devices and fog nodes, and ensuring that the network does not become congested.

With the help of network virtualization technologies such as GNS3 [11], the FDK reduces development costs by allowing edge-fog systems to be developed in a virtual network, and then subsequently ported over to a physical infrastructure with ease. Moreover, the FDK is designed to be used in unison with Open vSwitch [12], and performs network resource allocation using the OVSDB protocol [13]. With this, the FDK can run at full capacity on a completely virtualized network, consisting of Linux VMs serving as edge devices and fog nodes, and Open vSwitch VMs which handle the messages exchanged between the edge and fog layers. In turn, this means that any edge-fog application can be developed and prototyped on a consumer-grade personal computer at zero additional cost.

We evaluate the correctness and performance of the FDK by using a testbed consisting of eight edge devices, four fog nodes, and five OpenFlow switches. Our results show that the delay of resource allocation and deallocation is less than 279ms and 256ms, respectively, for 95% of edge-fog transactions. We also show the resiliency of the FDK by analyzing the impact of various network conditions and levels of congestion on already-running edge-fog application transmission speeds and show that bandwidth allocations are accurately enforced and upheld regardless of network conditions.

The rest of this paper is organized as follows. We present the related work in Section II. In Section III, we summarize the goals and features of the FDK. Section IV consists of an in-depth investigation of the system architecture and operation of the FDK. In Section V, we present the testbed setup and performance evaluation results. In Section VI, we highlight potential future work, and lastly in Section VII we conclude our work.

II. RELATED WORK

In this section, we overview relevant simulation platforms and justify the importance of the FDK. Also, we summarize existing load balancing and resource allocation schemes and identify their shortcomings when applied to edge-fog systems.

A. Simulation Platforms

Due to the significant cost of creating fog and cloud network infrastructures, many researchers and engineers measure the effectiveness of their platforms using simulation. In fact, many of the related works throughout this section rely on simulation-based evaluation [5]–[7].

CloudSim [14] is perhaps the most popular cloud simulation platform available, which is used for modeling the cloud and application provisioning environments. It is a discrete, event-based simulator written in Java, meaning that it does not actually emulate network entities such as routers and switches. Instead, CloudSim uses a latency matrix which contains predefined values for the latency between entities in a virtual network. Additionally, CloudSim can model dynamic user workloads by exposing a set of methods and variables for VM-level resource requirements, and is an all-around tool for simulating and testing new cloud systems.

There are also many extensions to CloudSim, such as CloudSimSDN [8], ContainerCloudSim [9], and iFogSim [10], which attempt to broaden CloudSim’s model to include SDN, Docker container migration simulations, and fog computing, respectively. However, because CloudSim and these associated extensions are strictly-simulation based, they ultimately do not solve the problems of cost and complexity associated with developing an actual edge-fog system. Rather, they simply avoid the problem altogether by simulating the entire system. Therefore, while CloudSim is a worthy platform for evaluating cloud architectures, load balancing algorithms, etc., it fails to actually serve as a valid edge-fog application development platform because projects developed in CloudSim are not portable to a real environment. Likewise, the same can be said for most other simulation platforms for similar reasons.

The FDK can be accessed at the following address: https://github.com/SIOTLAB/Fog-Development-Kit.git
B. Resource Management and Allocation

Resource management is key to the success of any edge-fog system, and consists of two main components: network resource management, and compute resource management.

Typically, network resource management is accomplished using a load balancer, which attempts to find a suitable path to one or more destinations while optimally spreading traffic throughout the network to avoid congestion. In many cases, Equal-Cost Multi-Path (ECMP) routing is used to manage network resources by distributing traffic throughout the network. However, several authors, such as Katta et al. [15] and Zhang et al. [16], suggest that ECMP’s performance is far from optimal and that it is known to result in unevenly distributed network flows and poor performance. In response, Katta et al. proposed Clove [15], a congestion-aware load balancer that works alongside ECMP by modifying encapsulation packet header fields to manipulate flow paths, ultimately providing lower Flow Completion Times (FCT) than ECMP. Similarly, Zhang et al. proposed Hermes [16], a distributed load balancing system, which offers up to 10%-20% faster FCT than Clove. While Clove can handle link failures and topology asymmetry, Hermes can handle more advanced and complex uncertainties in the network such as packet black-holes and switch failures.

Unfortunately, load balancers do not adequately fulfill the network resource management requirements of edge-fog systems. Load balancers simply find multiple paths for traffic distribution, whereas edge-fog systems need to actually reserve or allocate bandwidth along paths in a network to fulfill application demands, such as the real-time transmission of critical information like medical monitoring data.

However, there are mechanisms that utilize actual network resource allocation to provide timely and reliable services. Akella et al. [17] proposed a method for guaranteeing network resources and reliable QoS. They leverage Open vSwitch, OVSDB, and SDN technologies to create three tiers of cloud QoS levels – QoS flow-1, QoS flow-2, and QoS flow-3 – where each allocate some amount of bandwidth for a cloud-user service. This is performed by dynamically creating packet queues on switches along the communication path, followed by then creating OpenFlow flows on those switches that enqueue traffic belonging to one of the QoS levels onto the appropriate packet queue. Kumar et al. [18] proposed a mechanism to extend SDN infrastructure to be “delay aware,” by finding paths for network flows such that end-to-end delays can be guaranteed. To this end, they use a similar scheme where packet queues are dynamically created along a path. Then, strictly one flow table entry is created and assigned per queue, and all packets belonging to a critical network flow are forwarded to the appropriate packet queue associated with that flow. Then, they propose a path finding algorithm for each network flow, meeting desired delay and bandwidth constraints. The end result of their work is an efficient, delay-aware path selection algorithm that can guarantee delay and bandwidth for flows throughout the network.

On the other hand, compute resource management often involves the use of virtual machines (VM) and containers, which can be configured to use a specific, limited amount of resources. In this case, the hard-limit on computing resources implies that compute resource management is equivalent to compute resource allocation (unlike the case with network resource management and network resource allocation). The amount of resources allocated to a VM or container directly affects the execution time of tasks and services, and as such, the allocation of these resources is critical in ensuring the timely processing of essential data. Containers hold an advantage over VMs in the context of resource allocation in the fog, as they tend to be more lightweight and, more importantly, provide finer granularity in allocating resources. For example, when allocating processing power to VMs, the available options only allow for the specification of the number of entire CPU cores a particular VM can use. On the other hand, container technologies like Docker [19] provide command-line interfaces for specifying more in-depth options when running a container. For example, container options allow the specification of a fractional number of cores that can be used (e.g., 1.25 CPU cores), in addition to the proportion of CPU cycles that can be utilized, which enables more precise, granular control of resource allocation.

The management of containers is typically performed through the use of orchestration software, such as Docker Swarm mode [20] or Kubernetes [21], which provides functionality for remotely managing, instantiating, and shutting down containers. These container orchestrators currently serve as the backbone for computing resource allocation in edge-fog and cloud systems, and current research involves more advanced use cases, such as investigating and optimizing live container migration techniques [22]. This is critical to the success of such systems, as live migration may interrupt running services, degrading performance and increasing completion delays. Ansari et al. [7] investigated approaches to resource management and VM migration for edge-fog IoT applications in mobile networks. They proposed Latency Aware proxy VM Migration (LAM), which solely considers latency when assigning a fog colony to a mobile IoT device, and Energy Aware proxy VM Migration (EAM), which considers the energy consumption of colonies. They simulated LAM, EAM, and static VM allocation, compared all the three approaches, and discussed the tradeoffs involved. For simulation, they used EveryWare Lab’s user movement trace [23], which emulates mobile device movement patterns. However, the authors acknowledge the need to conduct further experiments on physical infrastructure.

C. Fog Architectures and Platforms

Resource allocation is key to the success of edge-fog systems, and many fog architectures involving automated resource allocation mechanisms have been proposed. Skarlat et al. [6] created a resource provisioning system for IoT services in fog networks using a fog-cloud middleware component. The middleware oversees the activity of fog colonies, which are micro data centers consisting of fog cells where tasks and data can be distributed and shared among the cells. This system merely manages fog computing resources, and it does not
allocate those resources, nor does it perform any allocation of network resources.

Yin et al. [5] built a novel task-scheduling algorithm and designed a resource reallocation algorithm for fog networks, specifically for real-time, smart manufacturing applications. However, unlike the previous work, a management software component is not used in their approach, and each fog node is burdened with the task of deciding whether to accept, reject, or send requests to the cloud. Resource reallocation is periodically run on a single fog node, reallocating resources among tasks in order to meet delay constraints. Their results show reduced task delays and improved resource utilization of fog nodes. Their experiments are strictly simulation-based and the resource management scheme only includes a single fog node during decision making.

Finally, the work that is perhaps most similar to the FDK is ENORM: The Edge Node Resource Management framework by Wang et al. [4]. Upon startup of the system, an edge manager software installed on all edge nodes gathers and stores available system resources. Then, each edge node listens for resource requests from a cloud manager software installed on a cloud server. Each resource request starts with a handshaking process that eventually leads to the initialization of a fog application. In contrast, edge nodes in our proposed FDK do not receive requests, but instead create and send them to a FDK instance running on a centralized controller. If accepted, the FDK then leverages containerization and SDN technologies to perform both fog node and network resource allocation, ensuring timely execution of services requested by edge devices.

III. THE FOG DEVELOPMENT KIT

The FDK addresses all of the problems mentioned in Section II by serving as a standard edge-fog application development platform. It enables the creation and deployment of edge-fog applications in realistic environments, rather than just simulation. The FDK also provides a comprehensive SDN-based resource allocation scheme. The FDK’s features are discussed in greater detail throughout this section.

A. Resource Allocation

The FDK provides comprehensive resource allocation capabilities for edge-fog systems to ensure the requests made by edge devices are fulfilled in a timely manner. This is accomplished by providing a resource allocation scheme where both fog nodes’ computational resources and network resources can be sliced and allocated.

Automated resource allocation in the context of an edge-fog network offers several benefits. First, it ensures that the services requested by edge devices own a dedicated slice of the network and provides the possibility of guaranteeing network latency and bandwidth for edge-to-fog communications. Second, it ensures that fog nodes are not overwhelmed by edge requests to guarantee application processing deadlines. We believe that these two features are essential in many edge-fog systems because the main advantage of utilizing fog computing compared to cloud computing is seamless interaction between edge and fog nodes.

B. Virtualization

The FDK was designed to be used in unison with virtualization technologies in order to reduce the development and prototyping costs of edge-fog applications. Developers can use software tools such as GNS3 [11] to build a completely virtualized network of edge devices, fog nodes, and Open vSwitches running within Linux VMs. Another Linux VM can be used as the SDN controller, running the FDK and the SDN controller software OpenDaylight (ODL) [24]. The controller VM listens for service requests from edge devices. Then, the FDK fulfills any requests by allocating resources and instantiating containerized services in the fog. Therefore, users can begin developing edge-fog applications to issue service requests to the FDK when needed, using only a personal computer.

C. Portability

Edge-fog applications running on virtual topologies may need to be ported over to physical, production topologies once they are complete. To meet this need, the FDK is designed to be highly portable. Edge-fog applications written on top of the FDK are intended to be portable in their entirety to physical systems. In fact, as will be discussed in Section V, the FDK was initially developed and prototyped in GNS3, and then successfully ported to a physical infrastructure. The FDK only requires that the machine it is running on has Python 3, ODL, and the necessary ODL plug-ins installed. In addition, in order to take advantage of the network resource allocation capabilities of the FDK, the networking devices (switches, routers) throughout the topology must support the OpenFlow 1.3 and OVSDB protocols.

We used Open vSwitches as the networking switches in our testbed. Open vSwitch can be installed on any virtual or physical Linux machine. However, large vendors such as Cisco and Juniper Networks also carry OpenFlow 1.3 and OVSDB compatible switches [25], [26], which could allow for a port of the FDK and any edge-fog applications developed on top of it to a physical, production-grade network.

D. Application Independence

The key principle that the FDK is designed to fulfill is application-independence. That is, the FDK aims to support any general edge-fog application being run on top of it, in order to ensure that a variety of heterogeneous services can be developed using it. To this end, the FDK provides a messaging protocol for edge devices to request resources and instantiate specific containerized applications in the fog to handle the edge device’s processing needs. Conversely, the messaging protocol also provides methods to deallocate resources and terminate the containerized application. Therefore, as long as all resource requests follow this protocol, any edge-fog application can request resources and leverage the power of fog nodes.

2 We recommend a personal computer with a minimum of 4 CPU cores and 16GB RAM to create a moderately large topology in GNS3.
IV. SYSTEM ARCHITECTURE

The FDK is a user-space application, operating on a central controller, which oversees the operation of edge devices, fog nodes, and OpenFlow switches. The FDK interacts with ODL to control communication paths and manage network resource allocation, and also leverages the Docker containerization technology to remotely instantiate services on fog nodes with a specific amount of resources. The central controller architecture is shown in Figure 1.

ODL is an SDN controller software that enables remote management and configuration of networks. In the case of the FDK, these capabilities are leveraged using ODL’s northbound REST interfaces and Model-Driven Service Abstraction Layer (MD-SAL). At a high level, the MD-SAL allows developers to define data models for ODL software plug-ins and extend the functionality of ODL. These plug-ins provide additional northbound REST APIs. Invocations of these APIs then may utilize a variety of southbound network management protocols such as OpenFlow, NETCONF [27], and OVSDB, to ultimately configure or modify devices on the network. These invocations must also include a data body that is in accordance with the YANG data model [28] defined by the corresponding ODL plugin being utilized. Upon validation of the data body, it is pushed to the MD-SAL’s configurational data store, which reflects the desired configuration of the network. Then, the corresponding plug-in uses the information placed in the configurational data store to apply the desired changes to the appropriate network devices using southbound protocols and interfaces. Once applied, these changes are reflected in the MD-SAL’s operational data store, which presents the actual, physical state of the network. In effect, the MD-SAL allows for and supports the development of extensions to ODL, making it an extensible, modular, and versatile SDN controller that has the ability to grow and evolve over time. In particular, the FDK utilizes ODL’s comprehensive set of northbound REST APIs to perform network management using a variety of southbound protocols. For example, the FDK pushes OpenFlow flows to switches and then remotely configures the switches via OpenFlow 1.3 and OVSDB, respectively, even though the only interfaces accessed by the FDK are ODL’s northbound REST APIs.

Docker [19] is a platform that allows for building, sharing, and executing applications within containers. Each container is defined by an image file, which specifies its exact contents. Image files are typically stored in centralized repositories and are accessible by remote compute nodes. Docker deploys containers by downloading the image file from the remote repository, unless the image is already cached locally, and then subsequently instantiates the container using this file. Docker Swarm mode is a feature that allows for the management and orchestration of such containers on remote machines. Because these containers have specifiable resource allocation parameters, the FDK leverages Docker Swarm mode to provide fog node resource allocation capabilities and to instantiate containerized services for edge devices.

The FDK combines and builds upon the functionality of Docker and ODL using three manager objects that oversee the entire network and provide interfaces for querying data and manipulating the topology. These objects are detailed throughout the rest of this section.

A. Topology Manager

The FDK uses a TopologyManager component to query, update, and manage the network topology. The core APIs for this component are described in Table I. On startup, the TopologyManager first issues queries to the MD-SAL’s operational data store for data pertaining to the ODL OpenFlow plugin, the ODL node inventory, and the OVSDB plugin to gather data on the entire topology. The results returned by the OpenFlow plugin include information regarding all network devices (e.g., hosts, OpenFlow switches), in addition to data on the links connecting them. Meanwhile, the results returned by the ODL node inventory contain more in-depth information on the OpenFlow switches and their network interfaces, and provide information on the speed of the interfaces and how much data has been transmitted across them since ODL started. Finally, the results returned by the OVSDB plugin contain information pertaining to the configuration of OpenFlow switches on the network, and provide the information required to remotely configure these devices.

The TopologyManager consolidates all of the information returned by these calls within a single Topology object, which models the network topology as a graph. The links connecting the devices throughout the network are modelled as directed graph edges, with each one containing multiple data fields such as the current utilization of the link, the current bandwidth allocations on the link, and port identifiers at each of the
link’s endpoints. The nodes (devices) across the network are modelled as edge devices, fog nodes, OpenFlow switches, or ordinary hosts (indicating that they do not belong to any of the aforementioned groups) using a set of device type classes provided within the Topology object. The data stored for each device varies depending on its type. For example, each fog node object contains information such as the total amount of processing, memory, and disk resources on the device, which is later used by the FDK to slice the resources and prevent over-allocation. Similarly, the OpenFlow switch objects store information regarding their current configurations and the flows installed in their flow tables, which is later used by the FDK to shape network traffic paths and to manage the allocation of network resources. The TopologyManager, therefore, serves as a comprehensive directory of information pertaining to the state and structure of the network and the availability of resources across it.

After creating the Topology object, the TopologyManager creates a background thread to continuously update the network topology over time. This thread issues the previously mentioned queries to the ODL operational data store to gather information on the latest state of the topology. Then, the thread analyzes the differences between the returned data and the current Topology object, and updates the Topology object to more-closely reflect the topology information returned by ODL by making the appropriate changes such as adding links and/or nodes.

The TopologyManager also provides a large number of APIs for managing OpenFlow switches via the OVSDB management protocol. These interfaces provide capabilities for creating and deleting constructs such as packet queues, QoS entries, and ports, which are used by the ResourceManager component of the FDK when allocating network resources. It should be noted that all OpenFlow data and OVSDB data are originally returned as separate topologies by ODL, and there is no immediately-apparent way to relate data between the two. In the case of Open vSwitches, the MAC address of the bridge being controlled by ODL is returned in the query to the OVSDB plugin, which can then be converted to an OpenFlow node ID by stripping out the colons in the MAC address, converting the remaining hex value to a decimal value, and prepending “openflow:” to the remaining decimal value. The FDK then uses this relationship when storing data in Topology objects, and effectively merges the two separate OpenFlow and OVSDB data sets into the single aforementioned Topology object.

Finally, the TopologyManager provides a greeting server thread used to handle greeting messages sent by edge devices and fog nodes. Edge devices and fog nodes are configured to send greeting messages upon boot up. Each message contains a device type and a node ID field, in addition to some supplementary information. The device type field specifies whether the device is a fog node or an edge device, and the node ID correlates the device with one that was found in the MD-SAL operational data store. By building this association via greeting messages, the TopologyManager can identify all of the host devices in the Topology and establish if they are an edge device, a fog node, or neither. These associations are key to differentiating devices, and establishing what actions are appropriate to perform on a device. For example, the FDK only instantiates services on fog nodes, as such an action would not be appropriate for other devices. Section IV-C presents this mechanism in detail.

B. Flow Manager

The FlowManager component provides a comprehensive interface for the management of OpenFlow flows throughout the network. The core APIs for this component are described in Table II. First, the FlowManager provides a set of APIs to simplify the process of creating flow table entries on OpenFlow switches. For example, this component provides a method for creating a flow skeleton, which contains all of the basic fields needed to create the flow table entries used by the FDK to enforce traffic paths between edge devices and fog nodes. Then, the FlowManager’s flow-modification APIs can be utilized to further build and shape entries by adding flow actions, flow match fields and other constructs to a flow skeleton. For example, flows can be created to match packets by source and destination IP address (or additional identifiers). Upon a match, multiple actions can be applied to a packet such as transmitting it through a specific port (used to create network traffic paths) and placing it on a packet queue. Once a flow table entry is built, the FlowManager flow-creation APIs can be leveraged to push a newly-built entry to an OpenFlow switch, and its flow-deletion APIs can be used to later remove such entries.

C. Resource Manager

The FDK uses a ResourceManager component to manage and allocate all network and computing resources. The core APIs of this component are described in Table III. First and foremost, the ResourceManager maintains data regarding all resources available in the network. This is possible with the help of an agent running on every fog node which continually collects and relays information (such as processor and memory utilization) back to the ResourceManager over time. Similarly, the ResourceManager also repeatedly queries the ODL node

### Table II: FlowManager APIs

| API                  | Description                                      |
|----------------------|--------------------------------------------------|
| create_flow()        | Push OpenFlow flow to switch                     |
| delete_flow()        | Delete OpenFlow flow from switch                 |
| track_flow()         | Track flow information                           |
| untrack_flow()       | Untrack flow information                         |

### Table III: ResourceManager APIs

| API                          | Description                                              |
|------------------------------|----------------------------------------------------------|
| service_edge()               | Process edge requests, run the RDA, and instantiate containers |
| service_shutdown_request()   | Process edge shutdown requests, run the RDA, and shutdown containers |
| service_fog()                | Receive and process fog resource reporting messages       |
| resource_alloc_algorithm()   | Attempt to allocate all resources for requested service   |
| resource_dealloc_algorithm() | Attempt to deallocate all resources for a service         |
The resource allocation algorithm (RAA) invoked by the edge service request server uses a modified version of the Bellman-Ford shortest-path algorithm [29] in addition to some pre- and post-processing steps. The RAA is presented in Algorithm 1. The algorithm’s inputs are an edge device $e_i$, the resources requested by $e_i$, and complete topology data. The RAA begins with a pre-processing step, where it iterates over all fog nodes $f_j$ in the topology and assesses their available resources to create a list of request servicers $R$ (line 16), which is a list of fog nodes that have sufficient resources to fulfill the edge request. Afterwards, if no request servicers exist, then the RAA returns a failure response that is subsequently sent back to $e_i$ by the ResourceManager (line 18).

If request servicers exist, then the RAA continues and executes a modified Bellman-Ford algorithm to find the shortest path from $e_i$ to all other devices in the topology (line 19). This is outlined in algorithm 2. The Bellman-Ford algorithm is executed using edge weights of $1/A_{lk}$, where $A_{lk}$ is the total available, un-allocated bandwidth on link $l_k$. This statistic is tracked on every link throughout the graph, and is updated whenever any resource allocation or deallocation occurs. Moreover $A_{lk}$ is never affected by background traffic, which can vary over time, as a separate allocation for background traffic is made when the FDK initially starts. Using the path cost metric $1/A_{lk}$ results in using shorter paths with higher available bandwidth. Furthermore, if $A_{lk}$ is less than the bandwidth requested by $e_i$ or if $A_{lk} = 0$, then $l_k$ is discarded and not considered.

Once the modified Bellman-Ford algorithm is finished, it returns a distance vector $D$ and a parent vector $P$ to the RAA.
Algorithm 2: Modified Bellman-Ford Algorithm

```
Input:
e_i = Edge device requesting resources
B_{e_i} = Bandwidth requirement of request from edge device e_i
Complete topology and resource data (from TopologyManager)

Output:
Distance vector D
Parent vector P

1. \( N \) = Set of all nodes in topology
2. \( L \) = Set of all links (edges) in topology (each link contains the IDs of
   the ports at each end of it, in addition to the node IDs of those
   devices)
3. \( R_{lk} \) = Current bandwidth allocation on link \( lk \)
4. \( T_{lk} \) = Total bandwidth capacity on link \( lk \)
5. \( A_{lk} = T_{lk} - R_{lk} \) = Available bandwidth for allocation
6. \( D \) = Empty distance vector map
7. \( P \) = Empty parent vector map

8. for \( n \in N \) do
9. \( D[n] = \infty \)
10. \( D[e_i] = 0 \)
11. for \( i = 1, 2, ..., size(N) \) do
12. for \( l_k \in L \) do
13. if \( A_{lk} = 0 \) then
14. continue
15. \( W_{lk} = 1/A_{lk} \)
16. \( C_{lk} = D[l_k.srcNodeID] + W_{lk} \)
17. if \( D[l_k.dstNodeID] > C \&\& A_{lk} > B_{e_i} \) then
18. \( D[l_k.dstNodeID] = W_{lk} \)
19. \( P[l_k.dstNodeID] = l_k \)
20. return \((D, P)\)
```

Specifically, \( D[n] \) returns the distance (or cost) to reach node
\( n \) from \( e_i \). Meanwhile, \( P[n] \) returns the node \( m \) which is
reached just before the node \( n \) when traversing the shortest
path between \( e_i \) and \( n \), in addition to the link between \( m \) and
\( n \). To this end, \( P \) can be used to traverse and gather
information on the shortest path between \( e_i \) and any other
device in the network.

These two vectors are then used by the RAA in the
subsequent post-processing step. First, \( D[r_k] \) is computed for
all \( r_k \in R \) and a fog node \( f_j \in \mathcal{R} \), where

\[
D[f_j] = \min(D[r_k]) \quad \forall \ r_k \in \mathcal{R}
\]

is selected to serve the edge request (line 24). If \( D[f_j] = \infty \), then no paths with sufficient
bandwidth between \( e_i \) and any request servicers exist, and
a failure response is returned to \( e_i \) as a result (line 26).
Otherwise, the path between the request servicer \( f_j \) and edge
device \( e_i \) has a sufficient amount of bandwidth, and \( f_j \) is then
chosen to fulfill the request from \( e_i \). A unique port number
for \( f_j \) is then generated, which is later used in the RAA and
eventually returned to \( e_i \), allowing it to communicate with the
containerized service instantiated on \( f_j \).

After \( f_j \) has been selected, network resource allocation is
performed along the shortest path between \( e_i \) and \( f_j \). The
nodes along this path are accessed by traversing through the
parent vector \( P \). Network resource allocation begins with
the creation of bandwidth-limited queues on each OpenFlow
switch along this path. The ResourceManager accomplishes
this by making a call to the TopologyManager function
create_queue() that leverages OVSDB to create and con-
figure the queues (line 31). These queues only limit egress
traffic in the OpenFlow switches, and the bandwidth limit set on
these packet queues is equal to the bandwidth requested by the
edge device. Once created, these queues are placed on QoS
entries (created on startup by the TopologyManager) using a sim-
ilar TopologyManager function place_queue_on_qos() (line 32).
These QoS entries map to switch ports connected to
the network links along this path, effectively resulting in each
port having a set of packet queues that limit egress traffic.

At this point, flows still need to be created so that traffic
is placed on the proper queue and redirected along the
identified shortest path. Therefore, as the ResourceManager
installs packet queues on each OpenFlow switch, it also pushes
OpenFlow flows to them immediately afterwards by leveraging
the FlowManager flow-creation APIs. Each flow specifies a
set of actions. The first action redirects traffic between \( e_i \)
and \( f_j \) to the appropriate outgoing switch ports (containing
newly-created packet queues) in order to form the shortest
path between them. The second action enqueues packets on
the appropriate queues, thereby limiting transmission speeds
to the bandwidth allocation amount originally requested by
\( e_i \). Furthermore, these flows match packets based on source
IP address, destination IP address, source or destination port
number (depending on the traffic direction), and traffic type.
For communications from \( e_i \) to \( f_j \), the source IP address is \( e_i \)'s
IP address, the destination IP address is \( f_j \)'s IP address, and
the destination port is the port that was generated earlier just
after the completion of the modified Bellman-Ford algorithm.
Since these rules must apply to UDP and TCP traffic, two
flows of this format must be pushed to the switch – One for
UDP, and the other for TCP. Furthermore, for communications
in the opposite direction from \( f_j \) to \( e_i \), two additional flows
are installed where the source and destination IP addresses
are reversed, and the source port is set to be the previously-
generated port. Therefore, the overhead for reserving network
bandwidth involves the creation of two packet queues and
four OpenFlow flows on each switch along the shortest path
between \( e_i \) and \( f_j \).

The end result of this process is a reserved path for all UDP
and TCP traffic between \( e_i \) and \( f_j \) that is bandwidth-limited
by the queues along that path. This is visually highlighted in
Docker is shutdown. The network bandwidth is deallocated by deleting the appropriate short, OpenFlow flows along the reserved path are deleted, and then uses that data to free the appropriate resources. In detailing the resources allocated for the corresponding service, (RDA). The RDA will find the entry in location algorithm, which then runs the shutdown request server edge terminate a service, it issues a shutdown request to the track all allocated resources. Once an edge device decides to over time, it maintains a dictionary data structure A in building reliable, real-time edge-fog systems are endless. With this, the possibilities of multiple fog nodes and a variety of heterogeneous service requests at the same time, allowing it to leverage the power of multiple fog nodes and a variety of heterogeneous processing services simultaneously. That is, even if a single edge device has multiple services instantiated on the same fog node, and are all provided the same path throughout the network, the packets transmitted will use completely separate packet queues and therefore have independent bandwidth allocations. Furthermore, these packets will reach separate containers (even if the containers are all running on the same fog node), meaning that all allocations are completely isolated. This enables a single edge device to create an arbitrary amount of service requests at the same time, allowing it to leverage the power of multiple fog nodes and a variety of heterogeneous processing services simultaneously. With this, the possibilities in building reliable, real-time edge-fog systems are endless.

As the ResourceManager continues allocating resources over time, it maintains a dictionary data structure A used to track all allocated resources. Once an edge device decides to terminate a service, it issues a shutdown request to the edge shutdown request server, which then runs the resource deallocation algorithm (RDA). The RDA will find the entry in A detailing the resources allocated for the corresponding service, and then uses that data to free the appropriate resources. In short, OpenFlow flows along the reserved path are deleted, network bandwidth is deallocated by deleting the appropriate packet queues, and the containerized service in the fog node is shutdown.

One benefit of this network resource allocation method is that, because a unique port number is used in the match field of each flow, each edge device has the capability to make multiple requests in parallel. That is, even if a single edge device has multiple services instantiated on the same fog node and are all provided the same path throughout the network, the packets transmitted will use completely separate packet queues and therefore have independent bandwidth allocations. Furthermore, these packets will reach separate containers (even if the containers are all running on the same fog node), meaning that all allocations are completely isolated. This enables a single edge device to create an arbitrary amount of service requests at the same time, allowing it to leverage the power of multiple fog nodes and a variety of heterogeneous processing services simultaneously. With this, the possibilities in building reliable, real-time edge-fog systems are endless.

V. Evaluation

We initially developed the FDK on a single machine using GNS3, which emulated the virtual network shown in Figure 4. This network contains five OpenFlow switches, four fog nodes, and eight edge devices. Afterwards, we ported the FDK to the physical testbed depicted in Figure 5 to create the same network topology. In the testbed, each edge device is a Raspberry Pi Model 3 B+ running Raspbian Linux. Meanwhile, the fog nodes and OpenFlow switches are hosted on VMs running on two machines. Each machine includes two 16-core Intel Xeon CPUs and 64GB of RAM. One of the machines includes five 4-port Intel 82580 NICs to build the OpenFlow switches. Another 2-port NIC is paired with one of the aforementioned 4-port NICs to build a 6-port switch and connect it to the controller. The machine hosting the four fog nodes includes a 4-port Intel 82580 NIC, where each fog node is associated with a port. Each fog node and OpenFlow switch VM running on these servers uses Ubuntu Server 18.10 and leverage 4 CPU cores and 8GB of RAM. The OpenFlow switch VMs run Open vSwitch 2.10.0 and support both OpenFlow 1.3 and the OVSDB management protocol. Finally, the controller where the FDK is installed is hosted on an external server.

A. Edge-Fog Application Development Evaluation

In this subsection, we evaluate the edge-fog application development capabilities of the FDK by creating a set of sample applications in a virtual network environment provided by GNS3. Afterwards, we port them to our physical testbed, and then use these applications during the performance evaluation of the FDK.

The first application, called iperf-app, enables an edge device to communicate with a containerized service on a fog node to track all allocated resources. Once an edge device decides to terminate a service, it issues a shutdown request to the edge shutdown request server, which then runs the resource deallocation algorithm (RDA). The RDA will find the entry in A detailing the resources allocated for the corresponding service, and then uses that data to free the appropriate resources. In short, OpenFlow flows along the reserved path are deleted, network bandwidth is deallocated by deleting the appropriate packet queues, and the containerized service in the fog node is shutdown.

3A sample version of iperf-app can be found in the FDK GitHub repository. We recommend using this application as a template for building other applications.
node using iperf3 [30] tool. This tool generates UDP and TCP traffic and reports bandwidth utilization readings every second. In this sample edge-fog application, the fog node hosts an iperf3 server within a containerized service, and the edge device connects to the server with an iperf3 client. To develop iperf-app, we first created a Python script that hosts an iperf3 server using the iperf-python library [31]. We then packaged this script into a Docker image. This image is used to instantiate containers that run the iperf3 server script upon startup. Finally, we modified the iperf3 server script to communicate all bandwidth readings to a background process running on each fog node for performance evaluation purposes. This process receives the readings and saves them to the disk. On the edge devices, we created another Python application that issues a service request to instantiate the aforementioned Docker image as a container, starts an iperf3 client that streams data to the iperf3 server running in the container, and then issues a shutdown request once the iperf3 client terminates. The second application developed is sleep-app, which is similar to iperf-app except the edge device sleeps for a specific duration instead of running an iperf3 client. After the duration has passed, the application sends a shutdown request to the FDK and then terminates.

B. Verification of Resource Allocation

To confirm the functionality of the FDK, we issued service requests to the FDK from the edge devices and verified that resources were being allocated properly. To this end, we made temporary modifications to the fog-side Docker images that would consume as many resources as possible and then confirmed that the containers instantiated from these images did not exceed the resources allocated to them. For example, we modified the iperf-app in one test to spin up an infinite while loop script that consumed all processing resources. Then, by using performance monitoring tools such as top, we confirmed that the container did not exceed the allocation requested by the edge device. Similarly, we confirmed that network resources were appropriately allocated using the iperf-app, which revealed that bandwidth allocations were not exceeded.

C. Performance Evaluation and Testing

After the verification of the FDK’s resource allocation capabilities, we performed in-depth performance evaluations and tests on the FDK, where edge devices continually issue requests over time in various scenarios. To simplify the presentation of these results, we partitioned the edge devices into three groups. Referring back to Figure 4, we placed edge devices 1, 2, and 3 into Edge Group 1, edge devices 4 and 5 into Edge Group 2, and edge devices 6, 7, and 8 into Edge Group 3. This grouping helps us identify the effect of the FDK on network overhead, which may vary depending on the location of the edge devices. For example, consider a scenario where all the edge devices issue service requests concurrently. The OpenFlow switch connected to the devices in Edge Group 1, which is the switch closest to the controller, would be placed under higher stress than switches farther from the controller, such as the switch connected to the devices in Edge Group 3. In this case, all edge service and

Fig. 6: Empirical Cumulative Distribution Function (ECDF) graphs for Test 1a. In this test, edge devices issue service requests sequentially. Edge Groups closer to the controller (and therefore FDK) complete all of their operations slightly faster than those farther from the controller. This is due to the additional network delay and packet processing at each switch between the Edge Group and the controller.

Fig. 7: Empirical Cumulative Distribution Function (ECDF) graphs for Test 1b. In this test, edge devices issue service requests concurrently. Edge Groups closer to the controller (and therefore FDK) experience significantly faster service request fulfillment times compared to those farther from the controller. This is because the FDK processes requests sequentially.
shutdown requests, OpenFlow messages, OVSDB messages, Docker Swarm container instantiation messages, etc., would pass through the switch connected to Edge Group 1. At the same time, only a fraction of these messages would pass through the switch connected to Edge Group 3. From this, we can conclude that each Edge Group may experience different service interruptions, given that the network conditions for each of them may vary. We created the three Edge Groups in an attempt to capture these variations. This way, we believe our results provide an accurate and complete picture of the FDK’s performance because different, realistic scenarios are investigated. The rest of this section outlines these experiments in detail.

1) Test 1: The goal of Test 1 is to characterize the computational and communication overhead of the FDK. This is accomplished by running edge-fog applications across all edge devices and recording the runtimes of various operations under different circumstances. We track the durations of key operations including resource allocation (i.e., RAA), resource deallocation (i.e., RDA), edge service request fulfillment, and edge shutdown request fulfillment. Edge service request fulfillment refers to the total time it takes for an edge device to send a service request and receive a response from the FDK. Likewise, edge shutdown request fulfillment refers to the total time it takes for an edge device to send a shutdown request and receive a response from the FDK. For this experiment, we ran sleep-app across all eight edge devices in the topology and measured the duration of the aforementioned actions. We repeated this experiment 250 times for a total of 2000 sleep-app runs, and ran two different versions of this test, bringing the number to 4000. These different test versions are Test 1a and Test 1b, as follows.

Test 1a. In this test, the edge devices run sleep-app sequentially. For example, edge device 1 issues a service request, sleeps for 3 seconds after receiving service, and then issues a shutdown request. After completion, the rest of the edge devices perform the same operation sequentially.

Figure 6 presents the results of Test 1a. The duration of various operations are averaged out among the edge devices of each Edge Group and are then displayed as ECDF graphs. As seen in Figure 6, more than 95% of all resource allocation, resource deallocation, service request fulfillment, and shutdown request fulfillment operations completed within 0.33 seconds across all Edge Groups. In addition, resource allocation times and service request fulfillment times are nearly identical, as are the resource deallocation times and service shutdown fulfillment times. In this case, this means that resource allocation is the main source of overhead in the process of fulfilling service requests, and that resource deallocation is the main source of overhead in the process of fulfilling shutdown requests. Also, operations performed for devices in Edge Group 1 tend to finish slightly faster than those for Edge Group 2, which finish faster than those for Edge Group 3. This indicates that edge devices closer to the controller receive service faster, at least under ideal network conditions. However, the difference in timing is on the order of a few milliseconds.

Test 1b. In this test, the edge devices run sleep-app concurrently. In this case, all edge devices issue a service request to the FDK at the same time, sleep for 3 seconds upon receiving a successful response, and then send a shutdown request.

Figure 7 presents the results of Test 1b. The resource allocation and deallocation results presented in Figures 7 (a) and 7 (b) are nearly identical to the corresponding Figures 6 (a) and 6 (b) from Test 1a, with 95% of these operations completing within 0.28 seconds across all Edge Groups. However, the results for service request fulfillment times in Test 1b, shown in Figure 7 (c), look considerably different compared to the corresponding Figure 6 (c) from Test 1a. Here, we can observe greater variations in our results, with Edge Group 1, Edge Group 2, and Edge Group 3 showing median service request fulfillment durations of 0.72, 1.06, and 1.71 seconds, respectively. However, there is far less variation in the results for shutdown request fulfillment times, as Figure 7 (d) shows. In this regard, Edge Group 1, Edge Group 2, and Edge Group 3 show median shutdown request fulfillment durations of 0.23, 0.24, and 0.25 seconds, respectively.

Because the service fulfillment process accesses and modifies complex data structures such as the Topology object representing the current state of the network, the entire process is guarded by a mutex. This means that the FDK queues concurrent service requests and handles them sequentially. This effect can be seen in Figure 7 (c). Here, because the edge devices in Edge Group 1 are closer to the controller than those in Edge Groups 2 and 3, service requests from these devices sit in a much smaller queue than the requests arriving later from Edge Groups 2 and 3. Similarly, the process of resource deallocation is also guarded by a mutex, meaning that multiple edge shutdown requests are handled sequentially as well. However, because the service requests are fulfilled sequentially, the sleeps and subsequent shutdown requests made by each sleep-app instance become slightly desynchronized and happen sequentially. As a result, we see a much smaller impact on shutdown request fulfillment times in comparison to service request fulfillment times throughout Test 1b. Consequently, while sequential request handling is generally fast, handling bursts of concurrent requests could be further improved by employing multiple controllers and synchronizing their operations.

2) Test 2: In Test 2, we evaluate the overhead of the FDK on the network. Specifically, we investigate if the FDK compromises bandwidth allocations (by reducing transmission speeds) for running edge-fog applications. We chose 1 edge device from each Edge Group to run iperf-app for 90 seconds with a 300Mbps bandwidth allocation. This is the maximum transmission rate of the Raspberry Pi Model 3 B+ edge device. Also, after subtracting transmission overheads such as packet headers, the actual transmission rate supported is around 280Mbps. For the 90-second iperf-app transmission duration, the edge device continuously streams data to a container running an iperf3 server in the fog. The iperf3 server then logs a bandwidth reading per second, for a total of 90 readings. Then, at 30 and 60 seconds into the 90-second iperf-app transmission, all 7 other edge devices in the topology run sleep-app for 1 second. This results in a group of service requests, shutdown requests, OpenFlow messages, OVSDB messages, and Docker Swarm container instantiation messages.
flowing throughout the network. We ran this experiment 100 times for the chosen edge device and repeated it for the other two chosen edge devices from the other two Edge Groups, for a total of 300 iperf-app runs and 4200 sleep-app runs. Finally, we used two separate versions of this test and analyzed their impact on network congestion and the transmission bandwidth of iperf-app. In the end, 600 iperf-app runs and 8400 sleep-app runs were performed. The two modified test cases, called Test 2a and Test 2b, are outlined in detail as follows.

Test 2a. Here, the sleep-app runs occur sequentially with a 2-second gap in between each run. Figure 8 shows the median value, as well as the upper and lower quartile values, for all 90 bandwidth readings of edge devices 1, 4, and 7. In addition to the stability of median values, the lower and upper quartile value markers in the figures are indistinguishable from the median value markers, indicating that transmission speeds are stable for the majority of the time during transmission. Moreover, although additional messages are flowing through the network at 30-50 seconds and 60-80 seconds, the transmission speed of iperf-app is not affected at all, indicating that the bandwidth allocated for each edge device running iperf-app is not compromised by the additional overhead incurred by the other sleep-app runs performed during this time. This experiment shows that a moderate amount of sequential edge service requests does not cause any service interruptions for transmissions in a single edge-fog application.

Test 2b. This test is identical to Test 2a, except that the sleep-app runs occurring after 30 and 60 seconds into transmission are executed concurrently. Figure 9 presents the results. Similar to the results of Test 2a, we see that there is essentially no drop or variation in bandwidth, confirming that a moderate amount of concurrent edge service requests does not affect transmission rates for a single running edge-fog application.

3) Test 3: In this test, we evaluate the effect of a large amount of concurrent requests on the service and transmission speeds of multiple edge-fog applications running in parallel. We subject the hardware to a stress test to measure how the FDK operates under large volumes of requests and to see if bandwidth guarantees can be reliably fulfilled in a highly-congested network.

For this test, we use edge devices 1 through 7 to run iperf-app concurrently. Similar to Test 2, a bandwidth reading is collected every second for each 90-second run of iperf-app. Then, at 30 seconds and 60 seconds into the 90-second iperf-app transmission, edge device 8 executes 15 concurrent runs of sleep-app at the same time. This process is repeated a total of 100 times, meaning that 700 iperf-app runs and 1500 sleep-app runs are performed. Finally, 3 different variations of Test 3 are executed, where different bandwidth allocations of 100Mbps (Test 3a), 200Mbps (Test 3b), and 300Mbps (Test 3c) are reserved for each iperf-app instance, bringing the total number of iperf-app and sleep-app runs to 2100 and 4500, respectively.

Once the tests completed, we calculated the average of each 1-second bandwidth reading across every iperf-app run within an edge group. For example, in the case of Edge Group 1, we initially had 3 bandwidth data sets consisting of 100 runs each (one for each of edge devices 1, 2, and 3), where each run consists of 90 bandwidth readings. We then took the average
of each bandwidth reading across every run to create a single
data set of 100 runs. For example, in the case of Edge Group
1, a reading from each run in this single data set represents
the average reading across the 3 devices in Edge Group 1 for
a specific time interval. Similarly, the same idea applies to
the devices and data for Edge Groups 2 and 3. It is worth
noting that we did not include edge device 8 in Edge Group
3 for this test, as it did not runiperf-app at all. Edge device 8
was excluded since it was already performing 15 concurrent
sleep-app runs and would have experienced a degradation in
performance if it were to runiperf-app as well. This is due to
the limited networking and processing capabilities of the
Raspberry Pi.

Figure 10 shows the results for Test 3. Here, we formatted
the results similar to those of Test 2, where markers for the
median value, upper quartile value, and lower quartile value
are displayed for each (averaged) bandwidth reading of every
run. Each sub-figure represents all of the data collected for an
entire Edge Group, and encompasses the 100Mbps, 200Mbps,
and 300Mbps versions of Test 3. Similar to Test 2a and 2b, the
lower and upper quartile values are nearly indistinguishable
from the median values, demonstrating very small variation
in bandwidth readings throughout the test. More specifically,
Figure 10 shows that the actual bandwidth readings are just
below the allocated amounts at all times, regardless of what
stress the network is placed under. As previously mentioned,
this is because of transmission overheads such as packet
headers, and not due to the FDK. In the case of the 300Mbps
iperf-app runs, there appears to be more variations in the
bandwidth readings than the 200Mbps and 100Mbps runs.
However, these variations do not correspond to the additional
messages flowing throughout the network at 30 and 60 seconds
into the 90-secondiperf-app transmission. As a result, we
believe these variations are due to the heavy processing load of
switches (their processing capabilities were nearly maxed out
during the 300Mbpsiperf-app runs). This is to be expected,
as the FDK bases a link’s total bandwidth capacity on the
smallest of the advertised speeds from the two interfaces at
each end of the port. So, if weak OpenFlow switches that
cannot meet the advertised speeds of their network interfaces
are used throughout the topology, the FDK cannot compensate
for this shortcoming and may end up over-allocation resources,
thereby compromising bandwidth allocations for edge-fog
application communications. Nevertheless, since edge devices
are resource-constrained and include interfaces with speeds
under 100Mbps, it is unlikely that such an issue will arise in
a more powerful, production-grade edge-fog network.

VI. FUTURE WORK

Despite the unique and extensive resource allocation capa-
bilities of the FDK, there are still improvements to be made
in the future. With regards to network resource allocation,
we plan to include transmission delay guarantees by adopting
approaches similar to [18]. Furthermore, the FDK does not
support smart resource negotiation with edge devices. This
means that if the amount of resources requested by an edge
device exceeds the resources available in the system, the
device simply receives a failure response message from the
FDK and cannot determine which resource demands should
be reduced or by how much. We plan on including available
resource information in responses to edge devices in the
future to promote flexible and more efficient service requests.
Moreover, it is not immediately apparent how an edge de-
vice can calculate what amount of resources is appropriate
to request. For example, determining the actual amount of
memory and processing capabilities required to execute an
edge-fog application in a timely and efficient manner depends
on various factors such as data processing algorithms, the
rate of data generation, and the sensitivity of application to
delays. As such, a proven, efficient solution to this problem
is not immediately apparent, and will be key to enhancing
interactions and establishing a greater synergy between edge
devices and fog nodes. Also, as discussed in Test 2, there is
further work to be done on how the FDK can service periodic,
bursty service requests from edge devices in a timely manner.
To achieve this goal, in addition to employing multiple FDK
controllers, reliable and timely communication between the
controllers is necessary to coordinate their operations.

The FDK opens up vast possibilities for the research and
development of new edge-fog systems such as image classi-
fication, medical monitoring, and industrial monitoring and
process control [32], [33]. In addition to the enhancement
and evaluation of the system’s building blocks (e.g., resource allocation algorithms and live container migration), further experimentation can be performed using the FDK on physical network infrastructures to identify the shortcomings of existing works as well as developing production-ready solutions.

VII. Conclusion

In this paper, we proposed the FDK: A Fog Development Kit for software-defined edge-fog systems. The FDK provides a comprehensive resource allocation scheme paired with automated routing policies, thereby offering a simplified and much quicker development cycle for edge-fog applications. Moreover, it stands ahead of other alternatives by providing support for both compute and network resource allocation. The FDK also significantly reduces the cost of edge-fog system development by supporting the use of virtualization technologies, and is designed to be highly portable to physical infrastructures. These features make the FDK a valuable tool in prototyping and developing any edge-fog system, as they can be created and tested virtually on mere personal computers, and then be easily ported to physical network topology. These capabilities differentiate the FDK from existing virtual simulation platforms, which do not support the development of such systems, but instead provide a means for testing and evaluating routing algorithms, container and VM migration policies, and fog and cloud management mechanisms. Since the FDK has been designed to be application-independent, it can be used to develop essentially any edge-fog application or system imaginable. By allowing edge devices to request an arbitrary amount of resources and services from the fog, it enables the development of large and complex edge-fog systems for essentially no cost, while at the same time abstracting and eliminating the complexity of resource allocation away from developers.

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