SDN testbed for validation of cross-layer data-centric security policies

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***Abstract*—Software-defined networks offer a promising framework for the implementation of cross-layer data-centric security policies in military systems. An important aspect of the design process for such advanced security solutions is the thorough experimental assessment and validation of proposed technical concepts prior to their deployment in operational military systems. In this paper, we describe an OpenFlow-based testbed, which was developed with a specific focus on validation of SDN security mechanisms - including both the mechanisms for protecting the software-defined network layer and the cross-layer enforcement of higher level policies, such as data-centric security policies. We also present initial experimentation results obtained using the testbed, which confirm its ability to validate simulation and analytic predictions. Our objective is to provide a sufficiently detailed description of the configuration used in our testbed so that it can be easily re-plicated and re-used by other security researchers in their experiments.**

***Index Terms*—Access control, communication system security, data security, information security, software-defined networking.**

I. Introduction

Data-centric security (DCS) is emerging as an architectural concept of choice for future military systems. The main objective of DCS is to provide protection on the level of individual information objects, as opposed to only at the boundary of a network domain. In order to provide this type of object-level protection, protection requirements and security policies need to be defined at the level of individual information objects, e.g., as postulated by the Content-based Protection and Release (CPR) [1] model. In addition, data-centric security policies need to address all three dimensions of data protection, i.e. confidentiality, availability and integrity (C-I-A) [2]. This is a substantial enhancement in comparison to traditional systems, where re-configurable security policies usually apply only to confidentiality requirements, while integrity and availability requirements are addressed only statically at the moment of system design. This approach limits the system's flexibility and is also not applicable to heterogeneous and dynamic systems, which are envisioned in the context of Federated Mission Networking [3]. In particular, modern military networks, in accordance with Tactical Interoperable Communications Standards (TACOMS) [4] and the Protected Core Networking (PCN) [5] concept, may consist of heterogeneous national systems, offering various levels of C-I-A protection mechanisms. Extending the enforcement of fine-grained data-centric policies to the network layer would not only enable the provision of appropriate C-I-A protection of data-in-transit in federated environments, but could also enable a better and more cost-effective utilization of network resource within systems operated by individual nations and NATO, e.g. by enabling the transport of non-sensitive information via links with lower confidentiality assurance level (and usually lower cost) while guaranteeing that sensitive data is transported via high-confidentiality paths.

Although fine-grained access control policies can be enforced at the application level with some well-known techniques [6], the enforcement of the object-level protection at other layers of the system, e.g. network layer, is less well studied. Nevertheless, the ongoing evolution of modern IT systems into *software-defined infrastructures* offers an opportunity to consistently enforce security policies across multiple layers of the system and with respect to the multiple dimensions of data protection, i.e. C-I-A. A particularly relevant technology in this context is software-defined networking (SDN) [7]. As it was proposed in [8], SDN offers a practical way of enforcing data-centric security policies at the network level.

Our main contribution presented in this paper is design of a low-cost flexible SDN testbed, specifically focused on the validation of cross-layer security mechanisms. As discussed earlier, such mechanisms are particularly important in the context of developing data-centric security mechanisms for software-defined infrastructure. Our testbed is based on open source components and enables high-fidelity implementation of various use cases present in a NATO operational environment. Thanks to the integration of software containerization,

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this testbed can easily support various application-layer scenarios, and include realistic background network traffic.

II. Related work

Several OpenFlow testbeds have been built for networking research and experimentation [9], [10]. The Open Federated Testbed (OFTB) [11] initiative offers the end users a low-cost access to experimentation testbeds focusing on key technologies for the network softwarization, including Software Defined Network, Network Functions Virtualization or cloud-edge/fog computing. However, most of these testbeds are mostly focusing on large-scale experimentation in networking protocols. Thus, they do not provide specific mechanisms for implementation of end-to-end application layer use cases and for the validation of cross-layer mechanisms.

Multiple research projects have used virtual network emulators to examine the proposed SDN security solutions. For example, in [12], a Mininet testbed was used to demonstrate the efficiency of FRESCO, an OpenFlow security framework that enables developers to implement, share, and compose together, many different intrusion detection and mitigation modules. In [8], a Mininet virtual testbed was used to assess the efficiency of a content-based protection and release mechanism that provides consistent enforcement of security policies across multiple system layers and multiple security dimensions in a software-defined networking environment. Jankowski in [13] presented the mechanism of network workload generation and its use for the evaluation of Monitoring And Detection of Malicious Activities System (MADMAS), an SDN-based intrusion detection system, in a simple virtual network.

However, low temporal fidelity significantly limits the usefulness of virtual network emulators. Therefore, the use of the Mininet for the evaluation of security mechanisms was mainly focused on proof-of-concept demonstrations rather than on assessment of key performance parameters, such as processing time, delay, jitter or application response time.

III. Testbed

The unique aspect of our testbed is that it is specifically focused on security experimentation in respect to security services provided by SDN to both the network and application layer. Our testbed can be also used to validate earlier results obtained analytically or from emulation (e.g. Mininet) and simulation (e.g. ns-3) tools. Indeed, due to the the envisioned combined use along with the ns-3 simulation models, the scale of the testbed can be limited, focusing on a flexibility of supporting various realistic application scenarios and enabling examination of performance of cross-layer security measures.

The testbed is physically installed at Gdańsk University of Technology in Poland. It consists of two types of computers: DS-UNO-30xx [14] and ECN-680A-H6 [15]. The current architecture of our testbed is shown in Figure 1. The topology is based on a simple example of a color-cloud topology as used within PCN or TACOMS. Although our current testbed was created mainly for research on Path Class Approach (PCA) mechanism [8], it is flexible enough to test many other security solutions for SDN networks, such as specific network-level intrusion detection systems [13].

An example of network topology, presented in Figure 1, consists of 7 switches (annotated $S1$ to $S7$), a controller, a server and a typical switch for VPN connection. It can be split into two networks: a control network (connections between the switches and the controller) and a data network (connections between the switches, including the server). There is also a VPN network allowing remote configuration of all testbed nodes via SSH protocol.

A. Configuration of OpenFlow switches

Switches $S1$ and $S4$ are installed on ECN-680-H6, while other switches are installed on DS-UNO-30xx. All switches use the Ubuntu 16.04 operating system and support remote configuration via OpenSSH connections.

Each switch has only two Ethernet built-in ports. As this was not enough to build the presented network, we used USB to Ethernet adapters (Edimax EU-4306) to add additional physical Ethernet ports. In Figure 1, connections annotated as *usb*eth* use USB adapters.

All switches in the testbed use OpenVSwitch 2.1.1-based (OVS) implementation of OpenFlow protocol in bridge configuration. In Figure 2, $S1$ bridge configuration is presented. Port names are the same as in Figure1. The meaning of *docker-host port* is explained in Section IV. An important advantage from a testing perspective is that any computer connected to the VPN network can be used as a controller.

B. Configuration of the OpenFlow controller

The controller is running on a DS-UNO-30xx platform. Similar to the switches, the operating system used is Ubuntu 16.04. In the current configuration, we use the Floodlight implementation of an OpenFlow controller, but it can be easily replaced by any other implementation of an OpenFlow controller.

C. Server configuration

As described in Section IV-A, thanks to the integration with a Docker platform, all switches can also be used as platforms to implement application layer functionality scenarios, including end-user hosts and simple application servers. However, in some scenarios that we would like to validate, it is beneficial from a performance perspective to include in the testbed a dedicated physical machine which acts as a server. Our dedicated Ubuntu 16.04 server is running on DS-UNO-30xx hardware. The server provides various application-layer services via HTTP, as well as other typical services such as FTP. For testing purposes, the PCA implementation described in Section III-D was used.

D. PCA-related extensions to the testbed configuration

In the PCA, enforcement of data-centric security policies at the network layer is based on use of a network layer identifier. This identifier determines the path that a data packet can take through an SDN network. As there may be more than one path

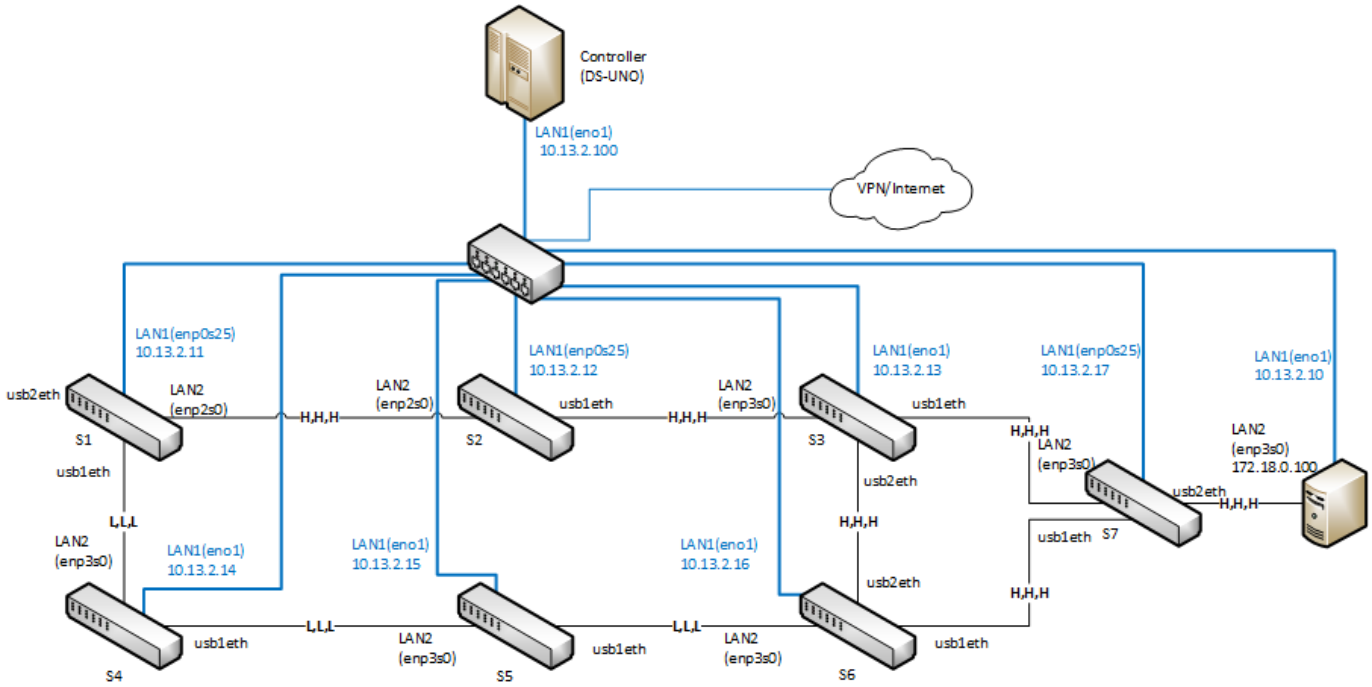


Fig. 1: Testbed architecture

```
root@switch1:~/scripts# ovs-vsctl show
bbf39bb4-1622-422b-9328-dd27725cdca6
    Bridge "s1"
        Controller "tcp:10.13.1.248:6653"
        Port docker-host
            Interface docker-host
        Port "usb2eth"
            Interface "usb2eth"
        Port "usb1eth"
            Interface "usb1eth"
        Port "s1"
            Interface "s1"
                type: internal
        Port "enp2s0"
            Interface "enp2s0"
```

Fig. 2: Switch 1 OVS bridge configuration

that meets the requirements of the CPR policy for a particular data packet, this identifier essentially determines a class of paths. Therefore, we refer to our approach, which implements CPR in an SDN environment, as the *path class approach*.

To test the PCA mechanism effectively, we have implemented several extensions to a standard SDN environment. Firstly, the OVS implementation was extended to support *PCA Link Attributes (LA)*. Secondly, a specific interaction pattern with a database application installed on physical server has been added. This pattern includes following elements:

1) A set of data objects annotated with metadata describing their attributes;
2) A corresponding CPR security policy, defining protection requirements for data objects based on their attributes;
3) A PCA Server Program calculating special identifier (Enforcement Action Identifier), which is used by the controller to obtain protection requirements.

The controller was extended with a PCA module, which is responsible for the programming of a route according to a defined CPR policy. All presented PCA mechanisms were described in [16].

The main new feature of the PCA module, which we have chosen for validation during our initial experiment in our testbed, was the dynamic estimation of the level of availability offered by each individual link based on their current usage.

IV. Scenario-based traffic generation

As mentioned earlier, one of the important objectives of our testbed is to support the validation of SDN-based security measures in realistic operational use-cases. Such validation requires the ability to perform experiments involving end-to-end real-time interaction between security policy enforcement points implemented at the SDN layer and CPR policies implemented at the application layer. This interaction needs to be performed in the presence of realistic operational network conditions. In order to achieve these objectives, we required the ability to expose each of the switches to a network traffic pattern, which is similar to a traffic pattern present in the particular operational application scenarios being investigated. In order to achieve this, two different approaches can be used. In the first approach, we would like to be able to quickly and dynamically deploy fully functional hosts or servers running applications involved in the validated scenarios, which would be connected to particular switches. In the second approach, we would like to run multiple network traffic generators connected to some of the switches in order provide a realistic background traffic for experimentation. In most of the experiments we envision the use of combination of these two approaches.

In order to meet our requirements, we have decided to install on each of the hardware nodes (except of SDN controller) the Docker software containerization platform[1]. In addition to providing an effective and lightweight software container deployment framework, Docker has also a potential to provide more reproducible research results [17].

A. Docker configuration

A Docker platform allows us to run lightweight software containers, emulating physical machines connected to a switch. It also enables us to eliminate the need for any physical connection of additional hosts, servers or traffic generators to the hardware nodes deployed in our testbed. As a basic container, we have used a customized Docker image based on Ubuntu 15.04 including following software:

1) Java Development Kit 8;
2) Ostinato Network Traffic Generator and Analyzer[2];
3) TCPDump; and
4) A custom application generating requests for protected documents stored at a server

```
root@switch1:~# docker network inspect sdn
[
    {
        "Name": "sdn",
        "Id": "9e013009170ef0731c763697d4a0267f59e74256f784
        "Scope": "local",
        "Driver": "bridge",
        "EnableIPv6": false,
        "IPAM": {
            "Driver": "default",
            "Options": {},
            "Config": [
                {
                    "Subnet": "172.18.0.0/16",
                    "Gateway": "172.18.0.1"
                }
            ]
        },
        "Internal": false,
        "Containers": {
            "eba7bb6db675f515a580dcfb69e90626f9cf309c1ca394
                "Name": "host",
                "EndpointID": "2816c7c18febede869527c6dd23e
                "MacAddress": "02:42:ac:12:00:0b",
                "IPv4Address": "172.18.0.11/16",
                "IPv6Address": ""
            }
        },
        "Options": {
            "com.docker.network.bridge.name": "docker-host"
        },
        "Labels": {}
    }
]
```

Fig. 3: Configuration of the additional Docker network

On each of the switches we have created an additional Docker network. This network is used to transfer data from Docker to OVS. Figure 3 depicts the configuration of this additional network. In the "Options" section of the listing, you can see that name of created bridge is *docker-host* which is the name of one of the OVS ports presented in Figure 2. As presented in Figure 4, in the Docker container, the port *eth1* is connected to an additional Docker network. This allows packets sent to the Docker container port *eth1* to be intercepted by the OVS switch and further transmitted according to the entries in the flow tables or, if no match is found in the local flow tables, to be sent to the controller.

```
root@eba7bb6db675:/# ifconfig
eth0      Link encap:Ethernet  HWaddr 02:42:ac:11:00:02
          inet addr:172.17.0.2  Bcast:0.0.0.0  Mask:255.255.0.0
          inet6 addr: fe80::42:acff:fe11:2/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:60 errors:0 dropped:0 overruns:0 frame:0
          TX packets:20 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:0
          RX bytes:12979 (12.9 KB)  TX bytes:1454 (1.4 KB)

eth1      Link encap:Ethernet  HWaddr 02:42:ac:12:00:0b
          inet addr:172.18.0.11  Bcast:0.0.0.0  Mask:255.255.0.0
          inet6 addr: fe80::42:acff:fe12:b/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:10617 errors:0 dropped:0 overruns:0 frame:0
          TX packets:3 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:0
          RX bytes:8914466 (8.9 MB)  TX bytes:258 (258.0 B)
```

Fig. 4: Configuration of network interfaces of a Docker container

B. Ostinato Network Traffic Generator

Ostinato was chosen as traffic generator due to its Controller-Agent architecture[3] and use of Streams[4].

In addition to port *eth1*, a Docker container is equipped with a por *eth0* (Figure 4), which is connected to a standard network created during the Docker installation (bridge). When starting a container, it is declared that the requests on the port number 7878 are to be transmitted to the container. This port is a standard listening port for Ostinato agent (drone) and forwarding of this port makes it possible to manage Ostinato agents on all containers from any computer connected to the VPN. Figure 5 shows the GUI of Ostinato controller running on a computer with VPN connections to the agent containers on switches $S1$ and $S2$.

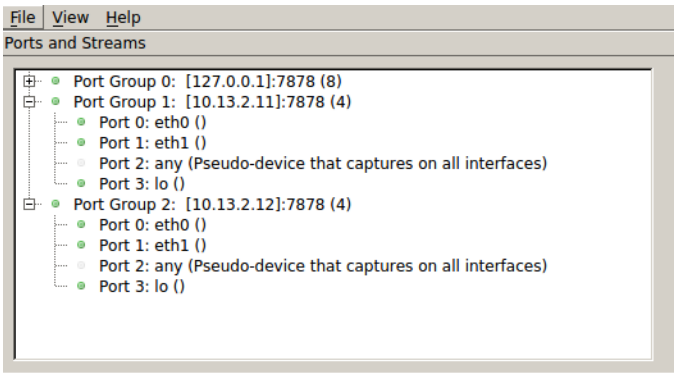


Fig. 5: Ostinato controller connected to $S1$ and $S2$

V. An example of PCA scenario

As mentioned earlier, a CPR policy can be used to capture all C-I-A protection requirements relevant to handling of the

[1]https://www.docker.com/
[2]http://ostinato.org/
[3]https://userguide.ostinato.org/Architecture.html
[4]https://userguide.ostinato.org/Streams.html

data of different layers of an IT system. In the context of SDN, C-I-A protection level offered by individual network links can be interpreted as a composition of static features of the links, i.e. strength of implemented cryptographic (for confidentiality and integrity) and redundancy (for availability) mechanisms implemented, as well as dynamic features, such as the current probability of each link being compromised, the amount of vulnerabilities present in the network equipment, as well as the current level of congestion at each link. Security state of each link is dynamic and can be influenced by both random faults and malicious actions.

As an example scenario, we will show the reaction of the PCA mechanism to a dynamic change in the level of availability offered by a link during a data transmission requiring a secure path. Such change can occur both as a result of network congestion and of a targeted denial-of-service attack. In our example, the security policy applicable to particular data type requires availability at the *HIGH* level, and confidentiality and integrity at the *LOW* level. Such protection requirements can be encountered in the context of civil-military interaction for example. It is important to note that *LOW* does not mean *none* - it is just an ordinal descriptor. All links between switches have a capacity of 10Mb/s. The background network traffic was introduced so that link utilization on each link was 20% (i.e. 2Mb/s). Table I shows the mapping between percentage of bandwidth consumption and availability levels.

TABLE I: Mapping of link utilization to availability levels

Bandwidth Consumption	Availability Level
0% - 50%	HIGH
50% - 75 %	MEDIUM
75% - 100 %	LOW

To download protected data, a *Host* (connected to $S1$) opens a connection to a Server (connected to $S7$). The shortest possible path ($S7-S3-S2-S1$) was chosen for transmission. During the transmission of protected data, utilization of the link between $S2$ and $S3$ is increased over time according to the chart presented in Figure 6 (see *Real Link Utilization* curve). Figure 6 shows also examples of tracking of real link utilization by the controller, where the time between updates on link utilization received by the controller is 2 seconds and 5 seconds.

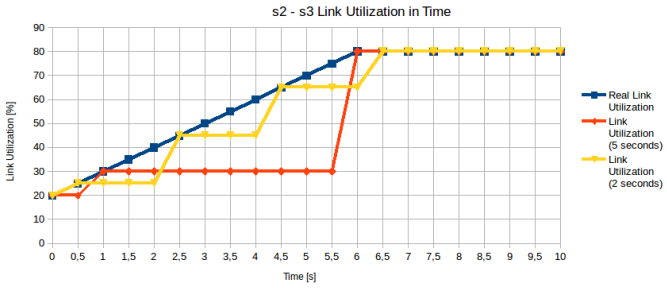
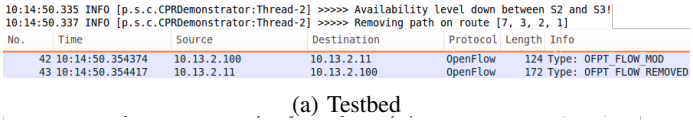


Fig. 6: Utilization of the $S2$-$S3$ link over time

As it can be seen, 3 seconds from the start, the increase of the link utilization exceeded 50% (5Mb/s), which caused the availability level to decrease from HIGH to MEDIUM. The decreased level of link availability is detected by the controller, which is followed by the removal of the currently used route from flow tables configured at the switches. The experiment was repeated using both the controller installed within the testbed and a remote controller connected to the VPN. Figures 7a and 7b show the time between the detection of a decrease of the availability level and the deletion of route from the flow table on $S1$. For the local testbed controller this time it is about 19 ms and for the remote VPN controller it is about 41 milliseconds. After removing the previously used route, the correct route is determined in response to another packet belonging to the stream containing the protected data.



(a) Testbed

(b) VPN

Fig. 7: Controller logs and OpenFlow packets on $S1$

We have also measured the delay between the moment a real link utilization exceeds the level required to provide adequate availability for a data stream and the moment when this fact is detected by the controller. For this measurement, we have used two different update intervals of 2 and 5 seconds respectively. Table II shows the time required to detect link degradation and to remove the link from the current transmission path for both update intervals and for two different placements of the controller - either in the local testbed or remotely via VPN. In theory, average times for detection should be 1 second and 2.5 seconds. This is confirmed by the experimental results, which also confirm that PCA mechanism works properly in the implemented testbed environment. It took nearly twice as long for a link to be removed from the current transmission path, in the case of a controller located remotely than it did in the case of a controller located directly in the testbed. This delay is caused by the distance (about 400 km) and several intermediate devices involved in the VPN connection. As a result, if a remote controller is used, twice as much data is potentially transferred over inadequately protected network path - e.g. in our configuration for a 1 Mb/s stream it means that about 22 kb of data is transferred in a manner that is not in accordance with its protection requirements. Our conclusion is that the location of a controller also affects the proper enforcement of security policy and may increase a risk of transmitting art of the information over an inadequate path.

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VI. Conclusions and Future Work

We have presented a low-cost implementation of a flexible SDN testbed, specifically focused on the validation of cross-

TABLE II: Time required to detect and remove non-compliant links as a function of the controller location and the time between updates

Location of the controller	Average reaction times		Time between updates
	Detect time [ms]	Remove time [ms]	
Local testbed	954	21,8	2s
Remote via VPN	1053	43,4	
Local testbed	2609	21,0	5s
Remote via VPN	2837	43,2	

layer security mechanisms. Such cross-layer security mechanisms are particularly important in the context of software-defined infrastructure and implementation of new security paradigms, such as data-centric security. Our testbed is based on open source components and enables the high-fidelity implementation of various use cases present in a NATO operational environment. Thanks to the integration of software containerization, this testbed can easily support various application-layer scenarios and include realistic background network traffic.

Using a simple scenario, we have demonstrated the functional correctness of the testbed, as well as its suitability to provide validation and additional insight into the behavior of analytically designed security mechanisms. In particular, we have confirmed that a physical testbed provides an effective environment for the evaluation of temporal features of security mechanisms. In our specific scenario, we have demonstrated that the location of a controller influences effectiveness of cross-layer security enforcement and may influence the amount of time when data availability cannot be guaranteed at the required level, thus increasing the overall security risk related to the utilization of the system.

We plan to extend our testbed setup to be able to demonstrate enforcement of security policies in respect to all three dimensions of data protection, i.e. confidentiality, integrity and availability. We also plan to perform experiments involving a combination of cross-layer and network-specific (e.g. network intrusion detection) mechanisms. We also plan to perform experiments targeting comparison of simulative and analytical results.

We believe that our testbed design can be re-used by other researchers in order to perform realistic experiments in a software-defined environment.

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