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journal or publication title	2021 IEEE 4th 5G World Forum (5GWF)
page range	505-510
year	2021-11-19
URL	<a href="http://hdl.handle.net/10228/00008836">http://hdl.handle.net/10228/00008836</a>

doi: <https://doi.org/10.1109/5GWF52925.2021.00095>

# Transpacific Testbed for Real-Time Experimentation

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**Abstract**—The transpacific testbed is a generic routing encapsulation (GRE) tunnel built between CUNY City College (CCNY), USA and Kyushu Institute of Technology (KYUTECH), Japan. The tunnel, built through internet2, originated from CCNY through the JGN network in Seattle and terminated at Kyutech in Japan. The testbed defines the future of the Internet by focusing on addressing research challenges associated with enabling trustworthy networks, supporting the Internet of Things (IoT), which encompasses everything connected to the Internet and cyber-physical systems (CPS) - a controlled mechanism monitored by computer-based algorithms. In this paper, we describe the setting up and testing of the testbed. Furthermore, we describe the real-time experiments conducted on the testbed and present the results. The experiments are classified into two: blockchain-based cooperative intrusion detection system (CoIDS) and Secure Virtual Machine introspection. In each of the experiments, we describe the method and present the result. Finally, we look into the ongoing works of extending the testbed to the COSM-IC global testbed.

**Keywords** — *Blockchain, Cybersecurity, introspection, virtual machine, Intrusion detection System, IoT, Internet, GRE tunnel.*

## I. INTRODUCTION

Recent developments in mobile networks, big data, and cloud computing lead to the growth of connected devices and Internet of Things (IoT) use cases. Various domains in which IoT significantly facilitates our daily lives include smart cities, remote healthcare, autonomous cars, security systems, and many others. One of the critical factors that satisfy the quality of service for these technologies is 5G mobile networks that rely on software-defined networking (SDN) and network function virtualization (NFV) [1]. New use cases, protocols, and technologies add new attack surfaces to the existing ones. An increasing number of cloud-based services across multiple geographical zones makes enforcing security and availability of the network services to the end-users more challenging. Traditional attacks such as IP spoofing, Denial of Service (DoS), Distributed Denial of Service (DDoS), etc., along with increased ransomware, spyware, and insider attacks, are targeting public and private organizations running on cloud-based servers.

To address these security problems and conduct real-world experiments on next-generation wireless technologies,

we developed a transpacific testbed between two labs located at the City College of New York and Kyushu Institute of Technology in Fukuoka, Japan. The project is part of the global development of an international networking and wireless testbed by federating US research testbeds including COSMOS, ORBIT, FABRIC, and PEERING with experimental facilities in Ireland, Greece, Brazil, and Japan. The federated international testbed was proposed to enable global experimental research on a wide range of optical, wireless, SDN and NFV, blockchain, interdomain routing, and edge computing experiments.

In this paper, we describe the testbed and present two real-time intrusion detection systems (IDS): blockchain-based cooperative intrusion detection system [2] and secure remote virtual machine introspection [3]. These real-time experiments have been successfully implemented and tested within the transpacific testbed. The blockchain-based CoIDS aims to establish a secure network by detecting a compromised node in a trust-chain networking structure. The architecture is novel because it securely shares attack information with nodes located in different sites in real-time with little dissemination latency. It also detects and prevents malicious activities on the stored data in real-time. The architecture is robust to public companies/nodes joining and leaving the blockchain network in real-time without any security concern. The architecture leverages the distributive and tamper-proof ability of blockchain to exchange attack signatures among participating nodes. The smart contract verification ensures that the architecture can thwart outsider and insider malicious activities while the performance metrics show its effectiveness when disseminating stored information. The other experiment implements a remotely secure virtual machine introspection (VMI) [3] using Artificial Immune System (AIS) algorithms. The application notifies system administrators about potential threats running in the VM in real-time via agentless operations. The monitored potential threats include keyloggers, rootkits, trojans, process hiding, and other intrusion artifacts. Experimental results of remote VMI on more than 50 different malicious codes demonstrated an average anomaly detection rate close to 97%. Based on the explanations, the contribution of the paper can be summarized as follows:

- To describe the setup and troubleshooting of a transpacific testbed between the United States and Japan.
- To describe how a blockchain-based cooperative intrusion detection system experiment is evaluated on the testbed and presents the corresponding results obtained in real-time.
- To describe how we set up a Secure Virtual Machine introspection on the transpacific testbed and explained the results obtained in real-time.

The remainder of this paper is organized as follows: Section II discusses the background and related works on the experimentation testbed, Section III describes the transpacific testbed. Section IV presents the experimentations and the results. Finally, section V describes the conclusions and ongoing future works.

## II. BACKGROUND AND RELATED WORKS

### Experimentation testbeds

Several works have been done on setting up the testbed for conducting experiments in intrusion detection and mitigation systems. The authors in [1] provide a detailed description of their testbed for deployment IDS in virtualized networks. Their setup is based on Mininet [4] to virtualize the network and ONOS controller [5] to manage it. To connect the controller and simulated IoT devices, they deployed an Open vSwitch [6]. In [7], the authors described setting up a highly reconfigurable cloud testbed to support research and education in experimentally assessing the practical impact of attacks and mitigations on realistic cloud systems. Compared to the previous authors, their testbed, known as Hyperdrive, runs on a combination of bare-metal hardware and virtualized systems. Authors cover experiments with constructing an access-driven side-channel attack that enables a malicious VM to extract fine-grained information from a victim VM running on the same physical computer. In [8], the authors illustrate examples of a low-cost testbed based on off-the-shelf hardware and open-source software to investigate security and privacy issues of many IoT devices, including HDMI sticks, IP cameras, activity trackers, smartwatches, and drones. Their research, supported by a large set of real experiments, indicates that many IoT devices have serious vulnerabilities. The Transpacific Testbed described in this paper is also based on a combination of bare-metal hardware and virtualized environment that provides a wide platform for conducting various security experimentations.

## III. TESTBED DESCRIPTION

The Transpacific testbed is a GRE tunnel through the internet2 that originates from the Center for Information Networking and Telecommunication (CINT) lab, CUNY City College, USA, through the JGN network at Seattle and terminates at the Kyushu Institute of Technology, Fukuoka, Japan. The testbed comprises two data-plane local area networks (VLANs) (VLAN 1091 and 1092) and one control plane VLAN (VLAN 1941) for experiments, as shown in Fig. 1 below. Each of the VLANs contains 254 private IP addresses and is replicated on each side of the testbed. In this section, we give the full description of each side of the testbed's setup.

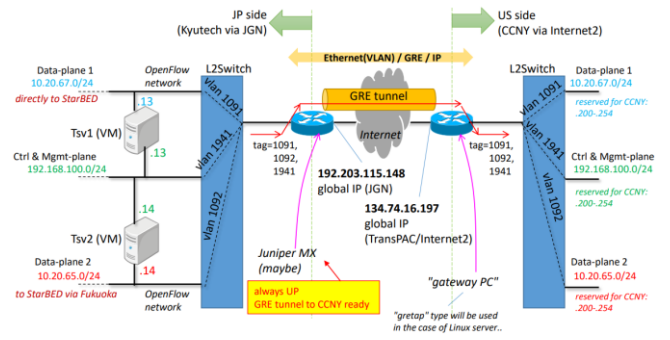


Fig. 1. The custom private blockchain

1. *CCNY Side*: The entrance to the CCNY side of the testbed has a dedicated PC that acts as a gateway to the network. The GRE tunnel is terminated at this gateway PC. The gateway PC has a network interface with a public IP address and another network interface that features a private IP address. The gateway PC is connected to a tagged port of a 4-ports layer2 switch. Each untagged port of the layer2 switch is configured to be a separate VLAN, as shown in Fig. 2. Each VLAN is connected to a multiport layer2 switch for experiments. The nodes used for experiments in this VLAN are connected to this multiport switch.

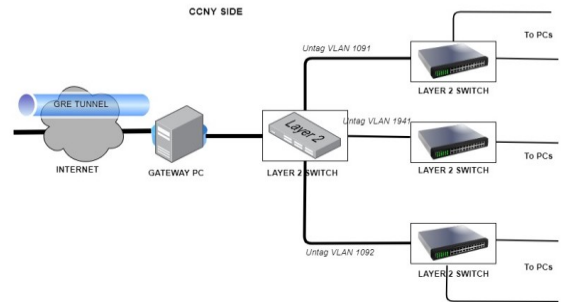


Fig. 2. CCNY side of the Testbed

2. *KYUTECH Side*. Unlike the CCNY side, the GRE tunnel at the KYUTECH side is terminated with a router. The router is the gateway to the network, and it is connected to the tagged port of the layer2 switch. Like the CCNY side, the untagged switch port is configured to different VLANs. Each VLAN port is connected to a multiport layer2 switch, accommodating multiple node connections for an experiment. Each of the VLANs 1091, 1092, and 1941 are replicated on both sides of the testbed. An experiment implementation conducted on VLAN 1091 can have part of the nodes set up in the USA while other nodes set up at the Japan side of the testbed, as described in section IV.

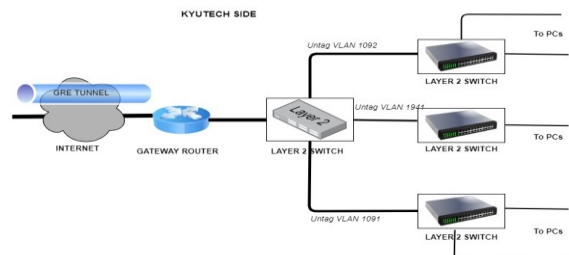


Fig. 3. KYUTECH side of the Testbed

*Testbed Testing and Troubleshooting:* After completing the connections between the sites. We performed connectivity tests and measured the throughput. To measure overall network performance and determine possible issues on both sides of the GRE tunnel, we deployed the *perfSONAR* toolkit (Performance Service-Oriented Network monitoring Architecture) [9]. The *perfSONAR* allows creating a grouping of tests, more commonly known as a "mesh." A shared configuration file written in the JSON format can be made with a graphical tool and published for other hosts to download. Each host then tests the different mesh members based on the configuration [10]. Using *perfSONAR*'s *scheduler* service, we made several automated tests to measure:

- Round trip time and related statistics between hosts
- TCP/UDP throughput in both directions (uses built-in *iperf3* utility)
- One way latency between hosts (uses *owping*)

Table 1 shows average TCP and UDP throughputs of incoming and outgoing traffic within the GRE tunnel after conducting more than 50 continuous tests.

Table 1. Average throughput between two labs after conducting more than fifty tests using *perfSONAR*.

Protocol	Source	Destination	Throughput (Mbits/sec)
TCP	CCNY lab	Kyutech lab	80
TCP	Kyutech lab	CCNY lab	75
UDP	CCNY lab	Kyutech lab	78
UDP	Kyutech lab	CCNY lab	72

During continuous automated latency tests, no packet loss was reported. Packet statistics and jitter measurements for every 1000 packets sent and received during one-way latency tests are illustrated in Table 2 below.

Table 2. One-way Latency Statistics (CCNY-Kyutech)

Data	Value (ms)
Delay Median	78.96
Delay Minimum	78.85
Delay Maximum	80.40
Delay Mean	78.97
Max Clock Error	0.13
Jitter (P95-P50)	0.06
Jitter (P75-P25)	0.04

## IV. EXPERIMENTATIONS

We describe two real-time experiments that are conducted on the trans-pacific testbed. For each of these experiments, we describe the objective, setup, and result.

### 1. Blockchain-based Cooperative Intrusion detection system

**Objective:** This work proposed a blockchain-based architecture that securely exchanges cyberattack signatures and features among participating nodes in real-time. This architecture allows companies to form a consortium and build a shared repository of up-to-date cyber attack features/signatures irrespective of their location. In this architecture, we leverage blockchain technology's tamper-proof ability, distributive nature, and data immutability to build a resilient solution to common cyberattacks on stored data. The architecture is novel because it detects and prevents malicious activities on the stored data in real-time. Also, the architecture facilitates a real-time attack signature/feature exchange. It is robust to public companies joining and leaving the blockchain network in real-time without any security concern. [2], [11], and [12] show some of the major publications from this work. Figure 1 below shows the pictorial representation of the experiment.

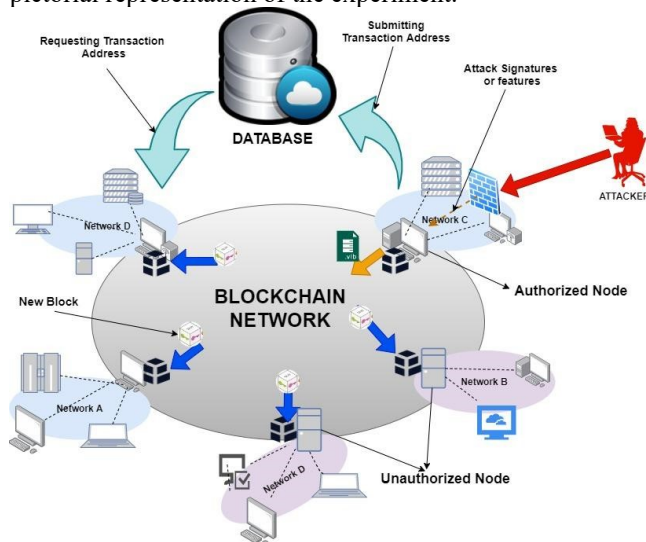


Fig. 4. Blockchain-Based CoIDS

The architecture, built on the Ethereum blockchain platform describes how the signature or features of detected attacks are retrieved, created into transactions, and submitted to the blockchain network for verification. It further describes the verification and validation steps of each transaction to detect malicious activities. A successfully verified transaction is attached to the blockchain, which is populated in the public ledger of other participating nodes. The participating nodes could download the stored information after obtaining the transaction information from the database. Finally, We evaluated the performance and security analysis using network dissemination latency, scalability, and ability to detect typical insider and outsider threats on stored data. For details of the architecture, refer to our previous works [2], [11], and [12].

The architecture has been tested in the laboratory. During the testing process, we performed both security and performance

analysis. We conducted some typical outsider and insider attacks in the security analysis to show how the architecture performs in real-time. The result showed that the architecture could detect and prevent malicious activities on shared information. Also, we evaluated the performance using the architecture's dissemination latency and scalability as the network grows. The dissemination latency defines the time it takes for the attack feature/ signature to be successfully distributed to all participating nodes after an attack has been detected. In contrast, scalability defines the effect of expanding the network (i.e., increasing the number of participants) on the architecture's dissemination latency. The laboratory results showed that the latency is very low (typically less than 2 seconds).

Despite the promising results, it is not easy to ascertain the architecture's behavior when deployed in a real-life scenario. The reason is that the architecture's testing platforms have light network traffic, which does not depict a real-life situation. We deploy the architecture to the transpacific testbed to evaluate the performance and observe the near real-life situation. Here, we set up part of the blockchain network on the CCNY side while the other domain is set up at KYUTECH, as shown in Fig. 5. The two fragmented blockchain networks are set up over VLAN 1091 and connected between the two sites, and we evaluated both the security and performance metrics. Testing the architecture across these inter-domain networks enables us to assess its scalability, throughput, and transaction dissemination latency over a wide geographical area with diverse network traffic. The deployment result gives the architecture's performance in terms of scalability, latency, throughput, and security if industries adopt the architecture.

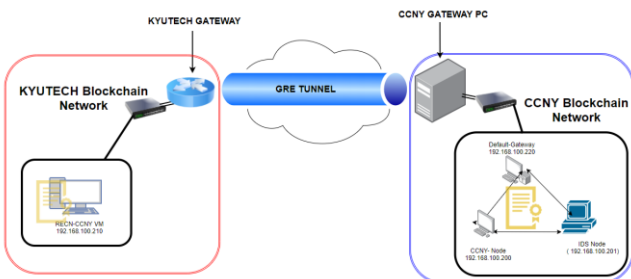


Fig. 5. The Blockchain-based CoIDS on the testbed

**Results:** Here, we show the preliminary result of the architecture's performance when conducted across the transpacific testbed. We used VLAN 1091 to set up each fragment of the experiment at each side of the testbed. Two blockchain nodes are set up at the CCNY side, while one resides at the KYUTECH side. The experiment was performed as described in [2]. We measured each node's dissemination latency and average dissemination latency. Fig. 6 shows the dissemination latency for blockchain nodes for twenty transactions. As explained in [11], dissemination latency is when a transaction is submitted to the blockchain to time each node retrieves the information from their ledger. This time comprises verification time, commit and mining time, new block broadcasting time, and time it is taken to retrieve it from their ledger. Fig. 7 shows the average dissemination time of each node. We can see that the average time spent on each node is low (less than 2 seconds), even for the node

located in Japan. For further work, we will repeat the experiment but with several blockchain nodes on each side of the testbed and compares the result to what was obtained initially.

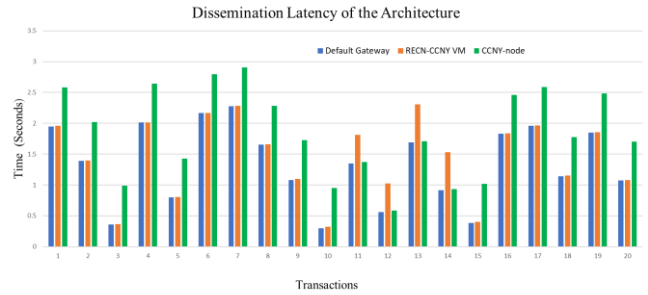


Fig. 6. The dissemination latency for blockchain nodes

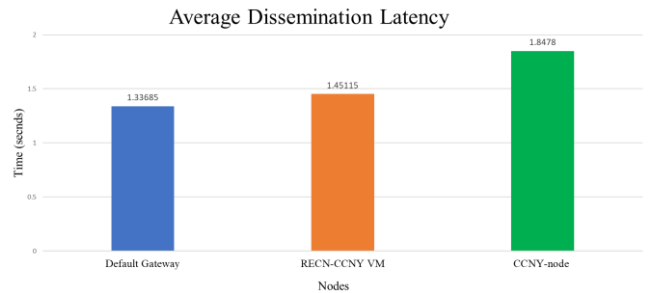


Fig. 7. The average dissemination latency of blockchain nodes

## 2. VM Introspection

**Objective:** The proposed work describes an Artificial Immune System (AIS) based Intrusion Detection System (IDS) that aims to introspect multiple Linux-based Virtual Machines (VMs) to detect malicious applications (such as keyloggers, spyware, rootkits, trojans, worms, etc.) while running from the outside of the infected VM. Developed software can reside on a client machine or operate directly within the host OS to continuously monitor multiple virtual machines. Once the suspicious process is detected based on anomalous behavior, the application in real-time notifies the system administrator and provides detailed information about the threat. Virtual Machine Introspection (VMI) addresses several security issues outside of the guest OS without relying on functionality rendered unreliably by advanced malware. The proposed application uses a lightweight VMI module *KVMonitor* [13,14], developed in C to access VM's memory file located in the host OS and get all the necessary information about processes running in the VM. A controller is a cross-platform application developed in Python that utilizes an Artificial Immune System algorithm, known as Negative Selection Algorithm, to collect the data and detect potential anomalies by tracking the events (*interrupts*, *memory writes*, *network activities*, and so on) [15].

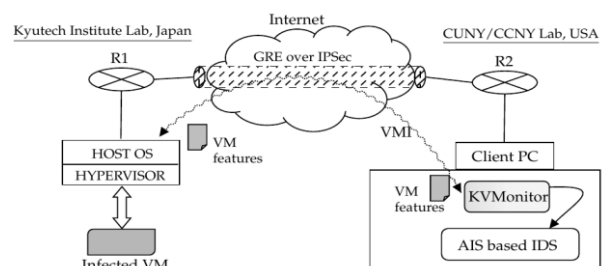




Fig. 8. VM introspection on the testbed

The overall architecture of the proposed application, as depicted below, provides security of cloud servers through automated virtual machine monitoring, intelligent analysis of network flows, and system-level process hidings, followed by mitigation actions being taken per the decision of intrusion detection component.

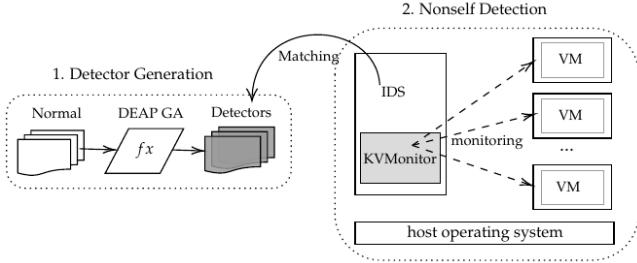
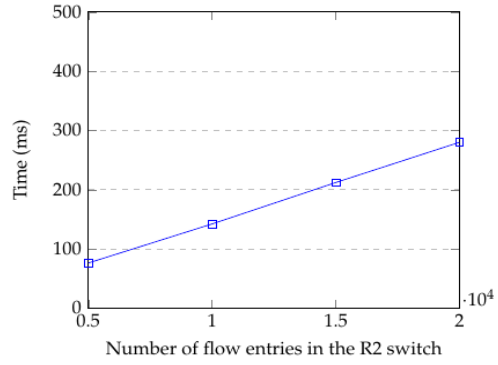


Fig. 9. Building blocks of the IDS

The end-to-end intrusion detection and mitigation process rely on two main steps: *Detector Generation* and *NonselF Detection*. As part of the first phase, using a *Genetic Algorithm* within the DEAP framework [16] and feeding it in advance with a set of normal features, the application generates a sufficient number of detectors. During this process, squared (Euclidean) distance is implemented as a fitness function to measure the distance between self and randomly generated nonself features. In the second phase, IDS constantly introspects multiple virtual machines and returns raw features. The application converts these values into the appropriate binary forms and begins the matching process. If the IDS finds a match for any incoming set of features among the detectors, it immediately notifies the administrator about a potential anomaly.

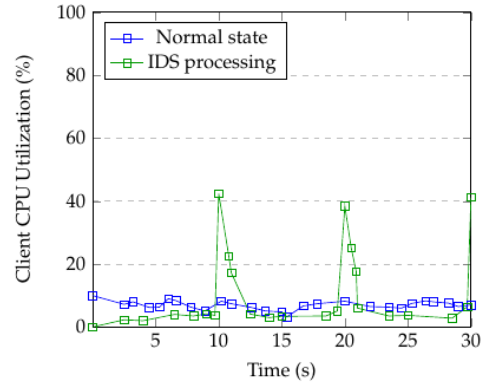
**Results:** Developed application has been initially tested on a local PC, with a pre-installed VM running within the same OS. After demonstrating high detection accuracy (F1 score 96.87%) and experimenting with over 50 different malicious applications, we started expanding this project to introspect VM launched on a remote host at the Kyutech. IDS has been successfully tested on remote VM through the established GRE-based secure testbed between the Kyushu Institute of Technology and the City College of New York. The maximum available bandwidth between the switch and hosts in our network is set to 100 Mbps. The packet sending rate was 1000 packets per second, and the payload of the packets was 1000 bytes. In that experiment, all features for 20,000 flow entries were collected in 416.4 milliseconds, whereas it was 280 milliseconds for retrieving the eight best features for the same number of flows. Remote VMI delivers a new way of securing cloud-based servers through the centralized controller. An IDS cannot be subverted by any malware running in the VM resides outside of the guest machine. This also provides a significantly low-performance impact on VM and the host machine.



Feature retrieval and processing time of 8 best features up to 20,000 flow entries.

Fig. 10 Features retrieval and processing time

IDS should retrieve attack features quickly for efficient attack detection and prevention. Feature retrieval time is significant, as there is no point in detecting attacks after they are over or have caused severe damage. Additionally, the feature retrieval process should not consume many client resources; otherwise, network performance would be adversely affected. We observe that the feature retrieval time increases linearly with the number of flow entries in the switch. However, our IDS performs feature processing on the fly and does not wait to finish every flow entry in the switch before taking action.



CPU utilization in the Client machine during normal state and IDS activity periods.

Fig. 11 Client CPU utilization for normal state Vs IDS activity

The figure above shows the CPU utilization on the host machine during the normal state and while KVMonitor accesses the VM memory file. Remote offloading was 8.5% slower than local due to network delay and additional booting time using VNC and SSH. During intervals of VM introspection, the CPU of the host machine correlated around 2.8 - 3.4%, which is normal because *KVMonitor* is only accessing the QEMU-KVM memory file stored in the host in *qcow2* format. First, *KVMonitor* obtains the value of the CR3 register in a virtual CPU of a VM by communicating with QEMU-KVM. For this purpose, we added a new CR3 command to obtain the value to QEMU-KVM because QEMU-KVM provides only the command for dumping the values of all registers in[14].

Conducted experiments on more than 50 different malware show the average F1 score (detection rate) of the nonself detection 96.86%. We divided experiments into two parts, first by exposing remote VM separately to each of the listed

malicious applications and measuring performance and detection time. Second, we exposed the remote VM to all four listed malware simultaneously and then launched our IDS. In both cases, anomalies were detected with almost similar rates, and IDS successfully responded on time.

## V. CONCLUSION AND ONGOING WORK

This paper described the setup and experimentation of a transpacific testbed between the USA and Japan. The testbed, a GRE tunnel through internet2, was built to define the future of the Internet by focusing on addressing research challenges associated with enabling trustworthy networks, supporting the Internet of Things (IoT), which encompasses everything connected to the Internet and cyber-physical systems (CPS). We described the tools used to evaluate the overall performance and troubleshoot. Furthermore, we described the two experiments that were conducted on the testbed and presented the results. The results show that blockchain-based CoIDS has a low dissemination latency. The proposed artificial immune system-based remote virtual machine introspection is promising for achieving real-time, highly accurate detection and mitigation of attacks in various cloud-based servers, where virtualization is the essential factor.

*Ongoing work:* As part of the ongoing work, the transpacific testbed will be extended to a NSF-funded COSMOS Interconnecting Continent global testbed (COSM-IC). The COSMOS Interconnecting Continents (COSM-IC) is a National Science Foundation (NSF) sponsored global testbed spanning Asia, Europe, South, and North America continents. The testbed proposes to develop capabilities that will enhance unique multi-technology and software-defined wireless, optical, and edge cloud network testbed infrastructure to perform a groundbreaking international collaborative experiment. The goal will be achieved by leveraging the COSMOS [RSZ+20, COS20] and ORBIT [RSO05, BCL14] testbeds' interfaces with the PEERING [SAC+19] and FABRIC [FAB20] testbeds and adding connections to leading testbeds worldwide, including CPQD (Brazil) [CPQD20], Kyutech U./StarBED (Japan) [Sta20], OneLab/NITOS (EU/Greece) [One20, NIT20], and CONNECT and Pervasive Nation at Trinity College Dublin (EU/Ireland) [CON20]. Currently, the global testbed is being built. After completion, the proposed experiments will be conducted on the global testbed Fig. 13. shows the extension of the transpacific testbed to COSM-IC

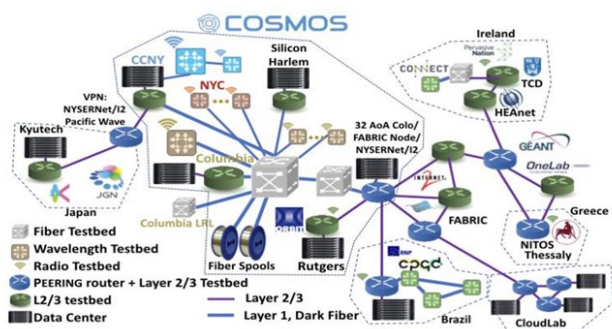


Fig. 12. COSM-IC global Testbed

## ACKNOWLEDGEMENT

This work is supported in part by NSF JUNO2 (*Japan-US Network Opportunity 2*) (Award No. 1818884) and NSF IRNC (Award No. 2029295).

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