Menes: Towards a Generic, Fully-Automated Test and Validation Platform for Wireless Networks

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1 INTRODUCTION

The use of wireless communication technologies has been increasingly popular since its first introduction with the analog radio over two centuries ago. Wireless technologies have been heavily used by the military by the end of the 1980s except for the radio and television broadcasting [33, 35]. With the introduction of cellular networks for citizens and development of wireless personal area networking (WPAN) technologies such as IEEE 802.11 [31] and Bluetooth [2], complex and heterogeneous wireless networks have been evolved. Apart from their wired counterparts, wireless networks tend to have higher mobility, heterogeneity, and higher dependence on the communication medium. It is, thus, important to develop robust wireless systems that can work under a wide range of circumstances. According to the Global Information Technology Report published by the World Economic Forum in 2016 [21], the median of mobile network coverage of 148 countries is 99% of the population, indicating that the cellular technology has advanced enough to cover a variety of different conditions such as extreme weather and altitudes. The high demand for mobile networks leads to complex network designs that require extensive test and validation processes.

As such, one of the main challenges of wireless network design is to understand how the design would perform in real-life scenarios. A naive way to test such a design is to implement and run all the required network components; yet, this is impractical for most of the scenarios considering modern networks can have thousands of devices or applications. Network simulation is one of the common techniques to avoid full-scale deployment of the network system. It models the network behavior by analytically analyzing the network components such as routers and user equipment. Most of the network simulation uses the discrete event simulation technique where the system is represented with state variables that change at discrete points of time. Network simulators such as NS-3 [12] have been widely used within different network technologies such as cellular networks (e.g., LTE), mobile ad hoc networks (MANET). Their major drawback, however, is that modern network systems become more complex to model by use of analytical methods. Further, modern network testing and validation also require the ability to run different third-party applications such as virtual network functions (VNFs) instead of just testing the proposed model. Network emulation, nonetheless, has the same goal with network simulation, yet allows users to run real applications. In a network emulation, users deploy the software intended to be run on the physical devices over the virtualized network devices. This allows users to test their application with neither deploying a full-scale real network nor analyzing the behavioral model of the network.

Albeit there exist a few well-known wireless network emulators such as Common Open Research Emulator (CORE) [20], they suffer several limitations. First, most of the wireless emulators lack configuration and deployment automation to run them to test and validate a variety of network types. Instead, they rely on experienced users to write complex configuration scripts to emulate the different type of networks, which makes the test and validation process be vulnerable to misconfigurations. Numerous studies on
network configuration demonstrate that human operator error can account for up to 70% of system failures [28]. Such failures, therefore, can increase the time for test and validate a network design and network configuration.

Second, existing solutions require a huge number of computing resources that might not be accessible by most of the users. For example, the Anglova tactical scenario, developed by NATO IST-124 Research Task Group, has a scenario that contains 283 highly mobilized network nodes [37]. The NATO IST-24 has deployed the Anglova scenario on the US Army Research Laboratory’s Dynamic Allocation of Virtual Clustering Management System (DAVC) with the Extendable Mobile Ad-hoc Network Emulator (EMANE) [36]. They run a virtual machine (VM) for each network node in the Anglova scenario with a VM for the controller node, requiring to capability to deploy 284 VMs. Unfortunately, running such a large number of VMs requires at least a small scale datacenter which is not accessible or feasible for most researchers.

Finally, most of the wireless emulators focus on emulating the physical layer (L1) and the data link layer (L2). Despite the possibility of running network layer (L3) or application layer (L4) programs such as routing protocols (e.g., OLSR [23]) or network applications (e.g., iPerf [8]) within these emulators, they do not offer an integrated mechanism to deploy a fully-functional system without configuring each component separately. This leads inexperienced users to spend many hours learning each tool to test and validate their network design. Further, most users use simple testing mechanisms such as running routing protocols with predefined configurations or using basic network applications to check network connectivity such as the Ping [14] tool. Consequently, such users do not have to configure each component independently; rather, it is desirable to have a fully integrated solution that only requires a high-level configuration.

In this work, we present Menes, a generic, fully-automated test and validation platform that overcomes the aforementioned limitations of existing emulation systems. First, Menes allows users to reuse existing network emulators, consequently, leveraging state-of-the-art solutions. Thanks to recent developments in OS-level virtualization, Menes supports different levels of node virtualization, including containerization. This allows for reducing the cost of implementation as well as deployment and test duration. Menes, furthermore, supports a variety of network applications and a range of control planes that can be configured via a unified, high-level configuration mechanism. This, subsequently, allows users to configure Menes baring only the intended network behavior in their minds instead of configuring each component separately.

Menes contains several layers to achieve generality and full-scale automation. First, it has a base network emulator component that emulates the L1 and L2 behaviors of intended wireless technology. Users do not need to configure the base network emulator; instead, they configure Menes that automatically configures the base network emulator. Second, Menes supports a variety of routing protocols including OSPF [29], OLSR, OLSRv2 [22], and OpenFlow-based [24] Software-Defined Networking (SDN). Moreover, users can run multiple protocols on a single node. We specifically analyze such a use case in Section 4.4. As we run each network node on a fully virtualized Linux kernel, users can run any application that can run on a Linux-based system. We also provide a set of network applications including iPerf and Multi-Generator (MGEN) [11] that can generate TCP, UDP, and ICMP traffic. These applications then analyze the network behavior in detail including latency, throughput, and jitter.

Next, we provide an open-source implementation [25] of the system that has EMANE as its base network emulator, Docker [4] as its virtualization layer, Quagga [32] routing suite with support of OLSR, and OLSRv2 as routing stack, and contains state-of-the-art network performance measurement tools including iPerf, MGEN. Our implementation further runs a resource monitoring stack based on the Telegraf [18] server agent, Prometheus [15] time-series database, and Grafana [6] visualization software (TPG stack). The implementation contains 5K+ lines of Python 3 code where users only need to configure a single YAML [19] file and they can use any Linux machine with Docker support. Our implementation, moreover, allows users to run on multiple machines to support thousands of nodes as a Docker Swarm cluster.

Our extensive experiments show that Menes reduces the runtime of emulations by 4x compared to state-of-the-art emulation solutions and reduces the required number of servers by at least 2x up to 5x compared to state-of-the-art virtualization solutions. Our implementation of Menes, further, supports a wide range of routing protocols that including OLSR, OLSRv2, OSPF, RIP, BGP, and SDN, which are not supported by existing wireless network emulators. We further demonstrate that our solution decreases capital expenses (CAPEX) and operational expenses (OPEX) of network emulation over an order of magnitude and reduces the possibility of human configuration errors that causing longer test and validation times. Finally, we discuss a use case of our platform in one of our early work focuses on multiple control plane composition with possible future work.

2 MENES ABSTRACTION

In this section, we present an abstract model of Menes. We first describe our network model and then give details about different layers of Menes. We finally discuss how Menes achieves generality and full-scale automation with a single configuration interface.

2.1 Network Virtualization

We first discuss how we model a network within our Menes. Formally, we define a network as follows:

Definition 2.1 (Network). A network N is a weighted directed graph without multiple edges, where a vertex n is called a node an edge l is called a link.

Within a network, each node contains a set of functionalities defined by different network layers discussed in the following section. Further, the network links are defined within the base emulation platform. Menes creates a virtual connection between nodes using the link specifications given by the user. Menes allows users to define heterogeneous links that are different nodes might use different types of physical or data link layers. Moreover, the network can contain a variety of routing protocols and network applications where each node can instantiate a subset of these protocols or applications. For example, a 10-node network might contain both IEEE

1Throughout this paper, we consider the transport layer within the application layer.
Figure 1: The architecture of Menes. (a) A node has numerous layers responsible for different network layers. (b) A Menes host contains several virtual nodes connected via a network bridge. Menes is configured via its configuration interface and Menes Controller manages each node and the network bridge.

802.11 and 30 MHz very high frequency (VHF) radio, where IEEE 802.11 does not run any routing protocol while 30 MHz VHF radio runs OSPF.

2.2 Node Virtualization

Menes enables users to run a virtualized version of their intended network devices. Although our implementation in Section 3 focuses on container-based virtualization and Linux-based OSes for generic network devices, our design does not enforce any virtualization technology or OS. Menes manages each virtualized node via a network bridge configured with the base network emulator.

2.3 L1 and L2: Base Network Emulator

Apart from other network emulation solutions, Menes can run different network emulations within itself thanks to its modular design shown in Figure 1. This empowers us to leverage existing work on different wireless technologies, rather than implementing an all-in-one L1 and L2 emulation. We call the L1-L2 emulation within Menes as the base network emulator. Combining with the node virtualization technology, Menes connects and manages each virtual node via a network bridge.

2.4 L3: Routing

Menes abstraction allows running any routing protocol that can produce forwarding rules for either IPv4 or IPv6. The dataplane model requires routing protocol to specify (a) Destination (i.e., IP address), (b) Gateway (i.e., next-hop IP address), and (c) Out port (i.e., the interface which connects the node with the specified gateway).

2.5 L4+: Applications

Although we focus on network performance measurement and network resource control applications in our implementation in

![Figure 2: A simplified configuration grammar of Menes for a given network N](#)

Section 3, Menes abstraction allows users to run any network application that is capable of producing IP packets. In this aspect, we count the transport layers such as TCP and UDP as network applications. For example, our implementation uses the MGEN [11] tool to generate TCP and UDP traffic patterns.

2.6 Menes Controller and Unified Configuration

One of the major benefits of our system is its unified configuration system that allows users to have an abstract view of different network layers and their complex configuration mechanisms. Instead of individually configuring components of a network, users can define a high-level configuration. To this end, we define a grammar to specify high-level configurations shown in Figure 2. Our grammar contains base definitions for a network including nodes, topology type, link, and traffic patterns. It is can be extended with the configuration of third-party software; where users can also specify component-specific configuration within the Menes’s configuration grammar.

3 IMPLEMENTATION

This section describes the implementation of Menes based on its abstraction described in Section 2. Our implementation uses Docker containers for the virtualization of nodes in the network and EMANE as the base network emulator. In Section 7.1, we discuss a wired implementation of our system where we use Docker Networking as our base emulator. We have provided an open-source alpha version of this implementation on GitHub [25] and created documentation available at [26].

3.1 Node Virtualization with Docker

3.1.1 Building a Docker Image. Docker containers run OS-level images that are built automatically by reading Dockerfile which is a particular text document containing image building instructions. We model the Docker containers in a similar hierarchical way to the Menes abstraction in Section 2 rather than using a monolithic Dockerfile as shown in Figure 4. First, we define a Dockerfile to run EMANE individually based on OS image such as Ubuntu 16.04.
Figure 3: Menes implementation workflow. Each node runs the L1-L4 network stack in a Docker container. The nodes are connected via two Docker Network Bridges: (a) EMANE Bridge to emulate wireless connection (b) Management Bridge: To deploy and monitor the containers from Menes Controller. The Menes Controller configured by the users automatically generate configurations for each application. The users finally access the network performance results and monitoring statistics via Grafana.

The Dockerfiles in the second layer contain routing software, and we currently support OLSR, OLSRv2, and Quagga routing suite which provides implementations for BGP, OSPF, RIP. This layer can be also merged with a Dockerfile containing OpenVSwitch to run OpenFlow-based SDN control planes. The final layer contains numerous network applications, including iPerf, MGEM, and our TPG monitoring stack. Preserving this hierarchy, users can also change their base network emulator, routing protocol, or network applications.

3.1.2 Docker on a Single Machine. Menes can run on a single host machine that can run Docker and EMANE. Figure 3 shows the architecture of our implementation on a host machine, where each node is represented as a Docker container and connected via Docker Network Bridge. Each container runs a set of applications, Telegraf as monitoring software, and EMANE instance automatically configured via Menes Controller. The Docker Network Bridge itself also connected to a single EMANE process that generates the link events based on the user configurations. The Management Network Bridge, on the other hand, is a 1-hop network where each node is directly connected to the Menes Controller enabling us to configure nodes as well as reading the metrics from Telegraf via Prometheus. The Management Network Bridge does not have any effect on the EMANE Network Bridge that carries the experimentation traffic.

3.1.3 Clustering with Docker Swarm. Despite the recent advancements on multicore processors and multiprocessor servers, there is a practical limit on the maximum number of concurrent containers that can be run on a single server. We, therefore, extend Menes to support running on multiple servers to emulate large topologies. To do so, we run Docker on swarm mode where a server is selected as a controller that runs as a Docker manager and also runs the Menes controller. We then run the other servers as Docker workers that only run containers to emulate network nodes. This mode only requires users to configure their servers to accessible via SSH from the controller node and configure Menes with the management IP addresses of each server.

3.2 Network Emulation with EMANE

As we discuss in the earlier sections, each container has an interface that is connected to the EMANE Network Bridge in the host. Each EMANE process runs a set of Network Emulation Modules (NEMs) that are network stacks as interfaces. Figure 5 shows the different layers in a NEM and possible configuration options for each layer provided by EMANE.

3.2.1 L1: Physical Layer Emulation. The first network layer emulated with EMANE is the physical layer. EMANE supports pre-computed path loss files or dynamic event generation via EMANE Emulation Event Log (EEL) Generator. Menes uses EEL Generator and it extends this into two options. First, users can pick a pattern of events such as Poisson arrival events. Second, they can also give a precomputed events as such in the NATO IST-124 Anglova scenario. The Menes Controller reads these user configurations and feeds into
The forwarding plane, on the other hand, is the Linux routing stack by default. Yet, the users can also specify to run specific forwarding planes including virtual switches such as OpenvSwitch [30]. This, therefore, allows users to emulate not only traditional routing protocols but also modern SDN applications. In our implementation, we test this capability with a simple OpenFlow-based SDN controller.

3.4 L4+: Network Performance Measurement

In our *Menes* implementation, we mainly focus on network performance measurement applications as they are fundamental to test and validate a network deployment. To accomplish this goal, we use three state-of-the-art network performance measurement applications that can generate TCP, UDP, or ICMP traffic loads: Ping, iPerf, and MGEN.

We use Ping for simplistic network connectivity validation, where we use iPerf to generate TCP or UDP loads to test not only the connectivity but also throughput and jitters. MGEN, developed by the U.S. Naval Research Laboratory, is a sophisticated toolset that can generate real-time traffic patterns for both TCP and UDP applications.

3.5 Resource Management and Monitoring

One challenge in wireless networks is the fact that most devices have very limited resources. For example, a handheld device runs on a small lithium-ion battery that can only last for a couple of hours in communication. It is, therefore, crucial for network designers to understand the resource consumption of the applications they are running on the devices. To this end, we developed an automated resource control mechanism running each network node device and reporting back to the controller.

Our implementation is based on two state-of-the-art data collection and storage agent. We run Telegraf to collect and send metrics from network nodes to the *Menes* Controller which runs the Prometheus time-series database to collect and analyze the metrics. We further run Graphana with built-in charts and graphs for users to visualize the metrics stored in Prometheus.

3.6 Continuous Integration and Continuous Deployment (CI/CD)

One aspect of network emulation has an equivalent version of the real network and test each change in the network by the emulation first. To meet this goal, we integrate our implementation of *Menes* with Travis CI/CD service. Users can deploy Docker Swarm over public clouds such as Google Cloud, then, changing *Menes* configuration triggers auto build and deploy of the emulation with new configurations.

4 EXPERIMENTS AND EVALUATION

In this section, we demonstrate the benefits and use cases of our platform.

Our extensive experiments show that *Menes* reduces the runtime of emulations by 4x compared to state-of-the-art emulation solutions and can support a wide range of routing protocols that including OLSR, OLSRv2, OSPF, RIP, BGP, and SDN. We further demonstrate that our solution decreases CAPEX and OPEX costs.
4.1 Runtime Evaluation

The table shows the bootstrap time of a subset NATO IST-124 Anglova scenario with 30 nodes using the DAVC and Docker Swarm cluster on Google Cloud. As we see in the table, Docker Swarm can reduce the initialization time by 4x. This is because starting containers does not require to bootstrap the Linux kernel, which is required to start the VMs.

### Table 1: Average bootstrap time for a subset of NATO IST-124 Anglova scenario with 30 nodes.

| Cluster      | Average Bootstrap Time |
|--------------|------------------------|
| DAVC         | 123 s                  |
| Docker Swarm | 29 s                   |

4.2 Overhead Scaling

Figure 6: The number of hosts required to emulate full mesh networks with different sizes, where each host has Intel Xeon E5 @2.30GHz with 24 cores. (a) OpenStack [13] private cloud with 3 controller and 3 storage hosts. (b) Docker Swarm that assigns each CPU core to a container. (c) Docker Swarm allows each node to have up to 88 containers.

In this section, we demonstrate how our Menes implementation scales with the network size. Figure 6 shows three different scenarios with OpenStack and Docker virtualizations. In each scenario, we calculate the number of hosts required to run to emulate a given network size. Our results show that using Docker Swarm can reduce the number of required hosts by 2x to up to 5x.

4.3 Cost Efficiency

The second set of evaluation demonstrates the benefits of Menes considering CAPEX and OPEX of network emulation. We used TCO tool [17] to compute the total cost of running network emulation over a year, where we consider the cost in-house servers as CAPEX and cloud expenses and management expenses as OPEX. We consider two different deployment environments for our scenarios. First, we consider the case that a user deploys OpenStack private cloud where each server has 24 CPU cores. Second, we investigate a public cloud service provided Google Cloud [3], where each VM runs at the minimum possible resources (i.e., 1 vCPU with 2GB RAM at an hourly rate of $24.67). We then test the cost of the same scenarios that we described in Section 4.2 as shown in Figure 7.

4.4 Use cases

As Menes emerged as a part of our existing project in [27], it has been tested in numerous use cases. We mostly focused on MANET use cases for military including the emulation of the NATO IST-124 Anglova [37] scenario. We further deploy multiple control planes within Menes namely OLSR, OLSRv2, and OSPF with a centralized OpenFlow-based SDN controller. The experiments include use cases such as IGP Migration, fast-failure recovery, network verification; as well as, network stress testing where we run a couple of hundred control planes at the same time on the state-of-the-art network topologies such as Stanford backbone network [7]. We further use an implementation of Menes for wired networks that uses OpenvSwitch and Linux networking stack as its base network emulator.

4.5 Extensibility

A major promise of Menes is high extensibility thanks to its modular design. Although our implementation is limited to a set of software, the users can extend Menes according to their needs. Each component can be replaced with a counterpart. For instance, if a user wants to test a different routing protocol that our implementation does not have, simply modifying the L3 Dockerfile and adding auto-configuration scripts to the Menes Controller would be sufficient. We further discuss such an extension for wired networks in Section 7.1.

5 RELATED WORK

Network Emulators. There have been numerous tools developed for network emulation namely Common Open Research Emulator (CORE) [3], EMANE [36], and NetSim [34]. The CORE is a tool for emulating networks on multiple machines that can be connected to
live networks. It contains a graphical interface to manage topologies, and Python bindings to script the network emulation. EMANE, on the other hand, is a framework for real-time modeling of mobile network systems that focuses on physical layer wireless emulation. Network Emulation Modules (NEMs) in EMANE can be heterogeneously used with real and virtualized network stacks. It further provides an event-driven control bus and logging facilities. NetSim is a full-stack packet-level network simulator and emulator that has been used by civil and military use cases over a couple of decades. NetSim allows users to integrate new protocols or network devices by requiring lower cost and in less time compared to hardware prototypes.

**Virtualization.** Kernel-based Virtual Machine (KVM) [38] is the state-of-the-art virtualization module within the Linux kernel allowing the kernel to run as a hypervisor of guest virtual machines (VMs). QEMU [16] is a VM emulator that emulates the machine processor via binary translation of instructions, which provides a set of hardware and device models. QEMU and KVM can be used together in Linux host machines which can be integrated with hardware acceleration to achieve higher performance. OS-level virtualization, on the other hand, is the technology that allows the existence of multiple isolated user spaces sharing the same kernel with the host [39]. This technique is different from running VMs where each VM instantiates its own kernel. Linux Containers (LXC) [10] is a container platform integrated to the Linux kernel providing user space for simple applications to run over containers. Docker [4] is a set of the platform as a service product that also has OS-level virtualization to deliver software in packages in containers. It offers better isolation compared to LXC, and it further presents complex network capabilities. Kubernetes [9] is another system for automating deployment, scaling, and management of containerized applications that mostly focuses on micro-services. Further, major public cloud vendors such as Amazon Web Services (AWS) [1] offers application-specific virtualization such as serverless computing.

6 CONCLUSION

This paper proposes *Menes* a generic, fully-automated test and validation platform for wireless networks. *Menes* allows users to easily deploy and iterate homogeneous or heterogeneous networks using different physical layer technologies or routing suites. It further allows users to deploy real applications or Linux-based VNFs. It is one of the first wireless network emulators enabling users to deploy thousands of virtual network devices within minutes by use of less computing resources compared to traditional solutions.

7 RECOMMENDATIONS

This work introduces the idea of full-stack emulation of wireless networks that enables users to use high-level configuration mechanisms rather than configuring individual components separately. We give a base implementation of *Menes* that focuses on MANET use cases; yet, it lacks support for other wireless technologies such as cellular networks. Further, we only focus on network performance and resource monitoring in our implementation, and a further direction can implement the state-of-the-art VNFs within our emulation platform. Thanks to its modular design, the developers only need to add components and define how high-level configuration grammar would parse into the particular configuration of their component. In the following section, we discuss our experience in porting *Menes* implementation into wired networks.

7.1 Porting to Wired Networks

Although our work is focused on wireless networks, one aspect of our design is the modularity of the core network emulation component. As we discussed in Section 4.4, the core network emulation component can be replaced with a wired network emulator. As wireless networks are highly mobilized and more complex, we pick wireless emulation as the starting point so that our platform can easily work with wired networks requiring only to change its base network emulator with a wired network emulator such as Linux virtual networking stack.

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