Satellite Communication
Digital Twin for Evaluating Novel Solutions: Dynamic Link Emulation Architecture

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Abstract—This paper presents the design and architecture of a network emulator whose links’ parameters (such as delay and bandwidth) vary at different time instances. The emulator is used as a digital twin for satellite communication systems, in order to test and evaluate novel solutions before their final deployment. To achieve such a goal, different existing technologies are carefully combined to emulate link dynamicity, automatic traffic generation, and overall topology emulation. Since emulating asymmetric dynamic links (as required in satellite communications) is far from trivial, we provide a detailed design architecture for solving such task. Experimental results show the precision of our dynamic assignments and the overall flexibility of the proposed solution.

As the demand for interactive services, multimedia and network capabilities grows in satellite networks, novel software and/or hardware components should be incorporated [1]. As a consequence, the testing and validation process of these newly developed solutions is critical to validate design decisions as well as to reduce (and expose) potential operational issues before their final deployment in a real network [2]. However, thoroughly testing or qualifying application-level or transport-level software under satellite conditions is a challenging task due to several reasons, e.g., the difficulty of creating various network topologies, generating different traffic scenarios, and testing the implementations under specific conditions (network load or weather conditions that may affect the radio-physical links in satellite communications).

Ideally, such tests are expected to be performed on the original system (physical testbed) in order to replicate the conditions in which a service or protocol will be used at the highest level of fidelity [3]. Unfortunately, that is often very costly, not scalable and not always possi-
ble since real satellite networks are not easily available. A very well-known alternative method is the use of network simulators [4]. Through network simulation, researchers and practitioners can mimic the basic functions of network devices and study specific network-related issues on a single computer or high-end server. However, the adequacy of simulated systems is always in question due to the model abstraction and simplification.

At the same time, not simulation but emulation for the related networks can also be a solution [5]. Network emulation provides the necessary mechanisms to reproduce the behavior of real networks at low infrastructure costs compared with physical testbeds while achieving better realism than simulations since it allows the interaction with interfaces, protocol stacks and operating systems. Moreover, it allows to perform continuous testing on the final implementation without having to make any changes in the solution once deploying it in a real network. However, the emulation of dynamic networks i.e., networks whose parameters change, complicates the emulation architecture. For example, satellite communication links have different up/down bandwidth capacity, large delays (due to distant objects), and the links’ capacities may change due to external interference, propagation conditions (weather), traffic variations (due to the shared medium), or others. Therefore, it is extremely important to have methods that allow us to control key parts of the emulation over time, such as the generation of traffic or the link property (capacity, delay) reconfiguration in order to build a proper digital twin of the environment of interest which is the main focus of this work.

To cope with such requirements, we herein propose a dynamic network emulation and traffic generation which combines the functional realism and scalability of virtualization and link emulation to create virtual networks that are fast, customizable and portable. Note that, verifying that the digital twin behaves as the original system with respect to a set of (physical) properties is out of the scope of this paper. However, the interested reader may refer, for example to our previous work [6].

EMULATION ARCHITECTURE

In this paper, we discuss our emulation platform, whose main goal is building fast and flexible software-based scenarios to test and qualify novel algorithms or protocols while meeting requirements such as realism, reproducibility, and representativeness. The design is based on well-known state-of-the-art technologies, such as virtualization (both hypervisor-based and container-based) or Linux kernel features (namespaces). When combined efficiently, these technologies provide excellent capabilities for the emulation of a diverse set of network topologies alongside the dynamic links and interconnected network devices. The emulation platform design and architecture, shown in Figure 1, consists of several independent, flexible and configurable components. We describe each of these components in detail in the following paragraphs.

The Emulator Manager is the main component and the central processing unit. It has a single instance per physical machine and it is composed of several independent modules in charge of the management, deployment and verification of the emulator components for a given network description (input for the emulation). In addition, it is responsible for providing, within the same physical host, the containers or virtual machines required for each emulated device as well as their own emulated network specifications.

The Verification Module fulfills several tasks. First, since our emulation platform relies on state-of-the-art virtualization (or container-based) solutions, it is in charge of creating and maintaining a network model that later is used by other modules to implement the necessary infrastructure elements for each emulation. To achieve this, we utilize a formal network description (the interested reader may refer to [7]) that contains both, the properties of the network topology as well as various network parameters in terms of first order logic formulas verified throughout the emulation by a satisfiability modulo theories solver. Once the model is built, it allows to check the properties of interest against the emulator [6]. Finally, the module is also in charge of parsing and verifying the file to generate dynamic traffic scenarios between the components of an emulated network.
The Deployment Module is in charge of converting the previously generated network model into running instances of emulated network devices. In order to achieve this, the module makes use of the docker engine for the management and support of containers and libvirt for different virtualization technologies such as KVM, VMware, LXC, and virtualbox. At the first step, it takes the input specification (from the network model) and creates the required nodes with their corresponding images and properties. Each emulated node is deployed by means of a Virtual Machine (VM) or a container attached to its own namespace and acts according to the software or service running inside of it (as requested by the input specification). For example, if it is desired to run a virtual switch as a Docker container, the Deployment Module creates the proper container and executes the corresponding Virtual Network Function (VNF) via a docker image (e.g., Open vSwitch). Therefore, each node has an independent view of the system resources such as process IDs, user names, file systems and network interfaces while still running on the same hardware. It can also hold several individual (virtual) network interfaces, along with its associated data, including ARP caches, routing tables and independent TCP/IP stack functions. This gives great flexibility and capabilities to the emulator, it can execute any real software as in the real physical systems. At the last step, the module creates the links between the nodes to complete the emulation topology. The links are emulated with Linux virtual networking devices; TUN/TAP devices are used to provide packet reception and transmission for user space process (applications or services) running inside each node. They can be seen as simple Point-to-Point or Ethernet devices, which, instead of receiving (and transmitting, correspondingly) packets from a physical medium, read (and write, correspondingly) them from a user space process. veth (virtual Ethernet) devices are used for combining the network facilities of the Linux kernel to connect different virtual networking components together. veth are built as pairs of connected virtual Ethernet interfaces and can be thought of as a virtual “patch” cable. Thus, packets transmitted on one device in the pair are immediately received on the other device and when either device is down the link state of the pair is down too.

The Dynamic Link Module is in charge of establishing and modifying the dynamic properties of the links (between the nodes) during the emulation’s execution time. An asymmetric link between two nodes, as shown in Figure 2,
is emulated by a set of nesting queues; in the simplest case - two queues. At the first step, packets are queued or dropped depending on the size of the first queue. This queue is drained at a rate corresponding to the link’s bandwidth. Once outside, packets are staged in a delay line for a specific time (propagation delay of the link) in the second queue and then finally injected into the network stack. This module uses the Linux Advanced traffic control tc, to control and set these properties by using filtering rules (classes) to map data (at the data link or the network layer) to queuing disciplines (qdisc) in an egress network interface. Note that since tc can be used only on egress, traffic Intermediate Functional Block devices (IFB) are created to allow queuing disciplines on the incoming traffic and thus use the same technique.

The Traffic Generation Module is in charge of converting the dynamic description of the traffic (the interested reader may refer to [7]), into a timed sequence of network packets. This sequence is then introduced into the deployed nodes during the emulation. For the generation of network packets, the module uses nmap at each node, particularly nping, allowing to generate traffic with headers from different protocols. This is achieved by using virsh commands using libvirt for virtual machines or by passing execute commands through the Docker daemon (for containers). It is important to keep in mind that nping can be replaced for any other software to generate traffic. Additionally, multiple instances of the same or different traffic generators can be executed inside each emulated node.

Finally, the Monitoring Module retrieves and collects information from the nodes and their links. This information can be used by the verification module to update, enforce and verify the network model. Additionally, for our case study, this information is useful to change the bandwidth on demand (in fact this is known as demand assigned multiple access or DAMA).

EVALUATION

In order to showcase the dynamic link capabilities of our emulator, we present an experimental evaluation, varying different network parameters i.e., bandwidth and delay.

In order to showcase the flexibility of the link’s bandwidth assignment we configured it by demand, that is the link’s bandwidth gets assigned whatever the node requires up to a maximal allocation (as in satellite communications). The DAMA scheme is out of the scope of this paper, however, our intention is to show how easy is to manipulate the bandwidth assignment. The results are presented in Figure 3; as can be seen, the measured bandwidth (with the utility bmw-ng) varies considerably w.r.t. the demand.

In order to showcase the flexibility of the link’s delay emulation, we have varied the desired delay between 5ms and 100ms. The assignment was made randomly by setting the delay queue with a normal distribution (using the tc utility). The results are presented in Figure 4; as can be seen, the delays have been measured (with nping) and the histogram clearly shows a normal distribution, as expected. It is important to note that the measured delay can be higher than 100ms since the processing time of the equipment plays a role in the delay, as in the real system.

CONCLUSION

In this paper, we have showcased the design and architecture for a dynamic link network emulator, which is used for creating a satellite communication digital twin. The emulator is flexible and can emulate any existing software; additionally, it can dynamically change the link parameter values.

As for future work, we plan to incorporate more features to the digital twin so that it becomes more controllable and realistic, for example, we consider incorporating link state scenarios to qualify the solutions under different conditions (degraded links, weather conditions, etc.). Additionally, we plan to further pursue the verification (at run-time) in order to guarantee that the digital has great fidelity w.r.t. the physical system.

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Figure 2. Asymmetric Link emulation model

Figure 3. Varying emulated bandwidth by demand

Figure 4. Emulated delay histogram

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