Reproducible Computer Network Experiments: A Case Study Using Popper

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ABSTRACT

Computer network research experiments can be broadly grouped in three categories: simulated, controlled and real-world experiments. Simulation frameworks, experiment testbeds and measurement tools, respectively, are commonly used as the platforms for carrying out network experiments. In many cases, given the nature of computer networks experiments, properly configuring these platforms is a complex and time-consuming task, which makes replicating and validating research results quite challenging. This complexity can be reduced by leveraging tools that enable experiment reproducibility. In this paper, we show how a recently proposed reproducibility tool called Popper facilitates the reproduction of networking experiments. In particular, we detail the steps taken to reproduce results in two published articles that rely on simulations. The outcome of this exercise is a generic workflow for carrying out network simulation experiments. In addition, we briefly present two additional Popper workflows for running experiments on controlled testbeds, as well as studies that gather real-world metrics (all code is publicly available on Github). We close by providing a list of lessons we learned throughout this process.

1 INTRODUCTION

The ability to reproduce previous experiments is one of the most important aspects in scientific research. However, as scientific discovery is rapidly advancing, researchers are pressured to rush publication of new findings and breakthroughs. This is especially true in computer science and engineering where knowledge and technology have been advancing overwhelmingly fast and the push to publish new results is even stronger. Lately, however, there has been growing concern in this community about results that cannot be reproduced and thus cannot be verified [1]. There is increasing consensus about the importance of being able to reproduce research results to better understand conveyed ideas and further improve upon them. Computer networks research is not the exception and this community has also been paying attention to the issues of reproducibility in this domain [2].

In addition to validating the credibility of scientific papers and their results, reproducing networking experiments has also been used as a hands-on way to teach both fundamental and advanced concepts in computer networking [3]. When teaching a new topic, educators want students to engage in the particular subject matter rather than the daunting task of setting up an environment. This educational aspect could be improved by using a tool that would enable students and educators to easily create and modify end-to-end workflows to make learning more accessible to students. Another motivation behind making the case for experimental reproducibility in networking research is based on our own experience as members of an academic research lab. Often times junior students help and eventually may take over the work of more senior students who are soon graduating or have already left the university. Instead of reinventing the wheel, it is in the interest of the lab for the new students to improve and build on top of previous work while leveraging as much of it as possible.

One of the biggest setbacks in reproducing results is the complexity that comes with rebuilding the same environment in which the original experiment was conducted. Most of experiments in the field of computer networks rely on expensive hardware, deep software stacks and complex configuration setups. In this paper, we make the case for a systematic approach to experimental reproducibility by making use of reproducibility tools. A recently proposed reproducibility tool named Popper introduces a convention for creating experimentation pipelines which are easy to reproduce and validate [4]. In order to show the suitability of the Popper convention in the experimental networking domain, we document our experience of automating the two network simulation experiments presented in [5,6]. One of the main reasons we chose these two papers was because we had the help of the original authors available to us. This paper details our experience with the goal of serving as a reference to other researchers seeking a way to make their experiments reproducible. In addition, we briefly present two additional Popper workflows for running experiments on experiment testbeds and studies that gather real-world metrics. The code for these workflows available on Github. The contributions of our work include:

- Applying Popper in the domain of computer networks.
- A methodology template for others to create reproducible experiments in the three broad categories of networking studies: simulations, testbeds and real-world measurements.
- A list of lessons learned and best practices that we have identified, and that other researchers can use as a reference.

The remainder of the paper is organized as follows, Section 2 gives a brief introduction to Popper, the tool that is used to help make networking experiments reproducible. In Section 3, we describe the networking experiments that we reproduce using Popper as well as the network simulation platform we use, while in Section 4, we describe how each experiment was conducted originally, i.e., prior to using Popper's reproducibility model. Section 5 presents experimental results under Popper and compares them with original results. Section 6 describes briefly the workflows that correspond to experimental testbeds and to real-world measurement gathering. Lastly, in Section 7, we reflect on our experience and provide a list of lessons learned that we hope will help other practitioners working networking experiments.

2 POPPER

Popper is a convention for creating reproducible scientific articles and experiments [7]. The convention is based on the open source software (OSS) development model, using the DevOps approach to implement different stages of execution. The Popper Convention creates self-contained experiments that do not rely on libraries and dependencies other than what is already inside the Popper-compliant or "Popperized" experiment. To achieve reproducibility, Popper uses pipelines containing shell scripts that execute the original experiment. An example of set of steps that an experimenter can follow to help achieve reproducibility are the following:

1. Experimental design and workflow definition.
2. Selection of tools (including hardware) for the study.
3. Packaging of software environment using portability tools such as Virtualenv, Docker, Vagrant, etc.
4. Creation of experiment scripts and parameter sweeps.
5. Creation of analysis scripts using data analysis tools such as Pandas or R.

The Popper pipeline consists of five stages: setup, run, post-run, validate, and teardown. In the `setup` stage, the workflow would usually download all the necessary software to run the experiment. These files are, for example, data files, libraries, and other dependencies. This stage can also be in charge of allocating resources on a testbed. The `run` stage executes the script that is used to run the original experiment. The `post-run` stage is where a user would implement the post-processing of results obtained in the run stage. This stage could be used to open a log file that shows the results of the experiment or run a script that graphs and displays the results. The `validate` phase is where experimenters would implement code that automatically check the claims being made in their study. Lastly, the `teardown` phase might be used to release resources that were allocated on a remote testbed. We note that each experiment may vary and that not all stages are needed for every experiment (and they can also be named differently).

In our case, for example, the simulation experiments we reproduced were made to run in a virtual environment called Instant Contiki. For this reason, we needed a Popper pipeline that could run a Linux operating system. To achieve this, we used Docker, a DevOps tool that packages applications and environments into containers. Docker allowed us to create an image of the Contiki operating system that contained all the libraries and dependencies needed to run it as just one package inside our pipeline. This feature of Popper that allows the use of DevOps tools and does not strictly require the use of any particular tool, makes it an advantageous convention, which we will demonstrate in the sections that follow.

3 NETWORK SIMULATION EXPERIMENTS

In this section we do a brief survey of existing simulation platforms (Section 3.1). We then describe two published studies that we have reproduced (Section 3.2), followed by an explanation of the Popper pipelines that we obtained (Section 3.3). We then report on the results (Section 3.4). The code for this pipelines, which can be used by researchers as a starting point for their studies, can be found at https://github.com/msouppe/cmpe257_mobile_networks.

3.1 Network Simulation Platforms

There are a variety of network simulation platforms such as NS3, MiniNet, and Cooja. NS3 [8] is an open source discrete event network simulator that is widely used for simulation environments for network research. Its goal is to provide scalability and ease of use for a variety of networks. Mininet [9] is also an open source simulation tool that provides a virtual network for interacting with Software-Defined Networking applications using OpenFlow. Cooja [10] is a widely used network simulation platform that is specialized in evaluating wireless sensor network applications. Cooja is a simulation tool for the Contiki open source operating system, which is used for building and connecting wireless systems for the Internet of Things [10]. Although each of these network simulators is a popular choice in the networking field, the experiments we are working with are conducted in Cooja, as it allows for inclusion of simple radio propagation models.

3.2 Studies Reproduced In This Paper

3.2.1 TerrainLOS. The first experiment we have reproduced in this paper is based on TerrainLOS [5]. TerrainLOS is an outdoor terrain propagation model that aims to create a more accurate simulation of outdoor sensor network communication. Most simulation platforms either assume a completely flat terrain or tend to use very simplistic channel propagation models that do not represent realistic outdoor terrain conditions. To present a more accurate outdoor simulation model, TerrainLOS uses common geographical height maps, called Digital Elevation Models (DEMs). These data files are used in experimental evaluations to investigate communication between nodes under realistic conditions. TerrainLOS defines Average Cumulative Visibility (ACV) as a metric to characterize terrain. ACV denotes the average percentage of nodes that are visible in an area from all nodes on a map. For example, 100% ACV means that every node is visible to all other nodes, which further implies the presence of a flat terrain. In their experimental methodology, the authors of TerrainLOS define population as the percentage of nodes per location on a given map, e.g., a population of one means there is one node for every one hundred locations on the map. The ACV and the population metrics are used in evaluating network connectivity. Our experiments in this paper focus on automating the execution and re-execution of Experimental Connectivity simulation in [5]. The purpose of this simulation is to experimentally evaluate the accuracy of connectivity results based on the models earlier presented by the authors in [5]. The connectivity results are plotted using the Average Cumulative Visibility metric and population size.

3.2.2 Sensor Network Deployment Over 2.5D Terrain. TerrainLOS has been used to evaluate the sensor placement algorithm proposed in [6] that aims at optimizing visual coverage in deployments over 2.5D terrain. 2.5D terrain is defined as using 2-dimensional rendering techniques such as the sensor placement algorithm and using controls in 3-dimensional space such as the terrains. It is named 2.5D terrain as it is not quite 3-dimensional but it is using features of 2-dimensions and 3-dimensions. The proposed algorithm works as follows. Initially, a set of nodes is placed on a given region. Then, each node executing the algorithm moves around the terrain to optimize the collective visibility of the network. In the original paper, each new run of the experiment involved initializing a script with parameters such as number of nodes, intended transmission range of the nodes, and the desired terrain, then running the script, analyzing the results, and repeating these steps multiple times until the results are reasonable.

Additionally, the experiment in the paper required pre-installing an associated program containing a graphical user interface (GUI) that required familiarity with its features from the user. After extensive manual configuration and initialization of the parameters mentioned above, running the script and waiting for the final results was a repetitive and time-consuming task. Since each new experiment had to be configured and re-run a number of times for accurate results, the student or researcher had to be present in front of their computer throughout the duration of the process. Finding a way of automating this process and avoiding using a GUI was imperative.

3.3 Reconstructing Experiments Using Popper

3.3.1 TerrainLOS. TerrainLOS is intended to run in Cooja, the network simulator for the Contiki operating system. In order to run TerrainLOS, without using Popper, a researcher would have to go through several steps when attempting to replicate the results in [Sam's Paper]. First, they would have to download Instant Contiki, a development environment for the Contiki operating system, and install a virtual machine to run it. Once the user has logged in and started the Cooja simulator, they would have to download the necessary files, libraries, and dependencies needed to run the TerrainLOS propagation model. Lastly, they would have to create a jar file of TerrainLOS and load it into Cooja to run the simulations. This is a very time-consuming task, not to mention the very likely possibility of encountering errors upon attempting to run the project the first time. Similarly to our experience, the researchers or the reviewers of the project may find that after compilation there are a few necessary files or modules missing that were not part of the set-up instructions provided by the authors. However, opposed to our particular case, reviewers rarely have a chance to contact the original author of the experiment and receive step-by-step instructions or solutions to the encountered errors. For this reason, interpreting error messages is generally cumbersome if not impossible.

Popper provides a significantly more effortless way to reproduce someone's experiment without the need of having the original author explain the steps needed for the procedure. Usually, the author would tailor their code in a way that follows the Popper convention from the start. However, making an experiment Popper compliant in retrospect is possible as well. We want to show this by detailing the steps taken to make Experimental Connectivity simulation of TerrainLOS Popper compliant.

First, in the implementation of the Popper pipeline, two stages were generated – the run stage and the post-run stage. Although in this particular experiment the setup, validate, and teardown stages were not used, the workflow for other experiments may differ. In our pipeline, the run stage takes care of setting up the Instant Contiki and Cooja environment. Since Instant Contiki requires a virtual machine to run and Cooja is usually used with a GUI, the setup of the two was accomplished with the help of Docker containers. Docker creates an image of the Contiki operating system including the Cooja simulator. Once the virtualization of the Contiki system is finished, the main task of the run stage is to execute the author's script that takes ACV and population size as inputs. The original simulation experiment was run using population sizes of one, ten, thirty, and eighty, and ACVs ranging from one to hundred percent with increments of ten. The same input arguments are used for the reproduced experiment as well. After the script has been executed, the output of these runs is saved in log files, which are read in the post-run stage with another script written by the author. The results are then graphed and saved in an image file as output. As a result, the original experiment is "Popperized" and can be run by just simply executing the `popper check` command inside the experiment pipeline.

3.3.2 Sensor Network Deployment Over 2.5D Terrain. When first running the experiment [6], there were a few tools that had to be downloaded before getting the experiment to work. Java and Contiki had to be installed since those are the environments where the experiment runs. Once the environment was set up, the code for the experiment would run in Cooja. Then for every experiment to be run, a simulation file had to be configured per experiment manually. This part of the process can be very lengthy since each simulation contains numerous different parameters. After each simulation script has been configured, each script could be run within the simulator, then after a certain amount of time the final Cumulative Visibility value is obtained. In the Popperized version of the experiment, there are two stages in the pipeline - the setup stage and run stage. The setup stage builds a Docker container which creates the necessary environment for the experiment to run. Additionally, the setup stage creates simulation scripts for every experiment the user would like to run. In the run stage, each of the scripts that have been made from the setup stage are now run in the Cooja simulator.

Furthermore, in the Popper version the user only has to configure one file for multiple simulations where popper will run each simulation individually and then output the final results. The automated workflow for this simulation is as follows; first, the values of the parameters of the experiment have to be defined by the user. Second, a Docker container is created with the entire environment, modules, and packages for the experiment to run. In the third step, the simulation template gets pulled, from the pipeline created from the popper tool, and the fourth step creates N simulations that the user has defined. Fifth, those N simulations are run and lastly the Cooja.testlog are outputted into the output folder to further evaluate the final result. Listing 1 shows an example Popper pipeline for this experiment

3.4 Results

3.4.1 TerrainLOS. The simulation experiment titled Experimental Connectivity in [5] outputs a graph depicting the percentage of connected networks based on Average Cumulative Visibility and

Listing 1 Sample contents of a Popper repository.

```
paper-repo
| README.md
| .popper.yml
| pipelines
|    |-- myexp
|    |    |-- setup.sh
|    |    |-- run.sh
|    |    |-- post-run.sh
|    |    |-- scripts/
|    |        |-- sim_config.yaml
|    |        |-- sim_template.csc
|    |        |-- create_sim_files.csc
|    |    |-- simulations/
|    |    |-- output/
|    |     -- contiki/
|    |        |-- {java files for exp}
| paper
|    |-- build.sh
|    |-- figures/
|    |-- paper.md
|    |-- paper.pdf
|     -- references.bib
```

population size. This graph can be seen in Figure 2. Intuitively, population size of 80 has the highest percentage of connected networks from ACV ranging from zero to hundred percent. The authors of [5] explain that this is because a larger population can bypass obstacles in the terrain (e.g., mountain) more likely than a smaller population. For this reason, the percentage of connected networks drop as the populations size decreases.

In our reproduced experiment output, depicted in Figure 3, a similar graph is seen. The reproduced experiment is not an exact copy of the original. This is because the experimental simulation outputs for Experimental Connectivity are intended to be probabilistic and vary across multiple runs. It is possible to generate the exact graph using the original simulation logs from the author, but we wanted to showcase the re-execution of the pipeline from the start of the experiment. We still observe the general trend in the reproduced results. Population size of 80 produces the highest percentage of connected networks. Furthermore, as population size decreases, the percentage of connected networks decrease as well. This trend indicates a successful reproduction of the experiment.

3.4.2 2.5D Deployment on TerrainLOS. Similar to Experimental Connectivity, the results of [6] are obtained in a form of a graph. The output of the original paper can be seen in Figure 4, while the output of our reproduced experiment is shown in Figure 5. Figure 4 shows results for every data point calculated for the average of ten nodes in random starting positions on specified terrain [6]. Furthermore, the graph illustrates each communication radius from 130 to 170 with increments of ten for the given terrains.

In the graph in Figure 5, we can see that the outputs are not exactly the same. Some of the reproduced results do not have all of the terrains as in the original results because not all of the terrains were available while reproducing the experiment. Furthermore,

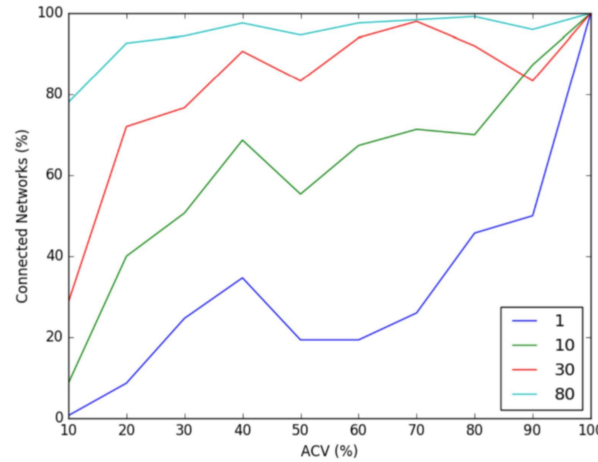

Figure 1: Original results from the Experimental Connectivity experiment in [5].

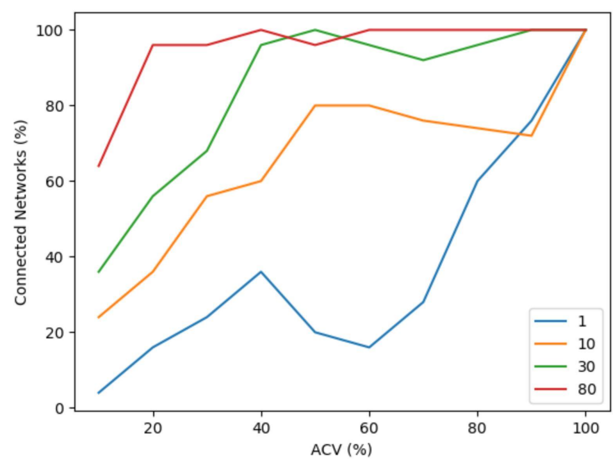

Figure 2: Reproduced network connectivity results using Popper.

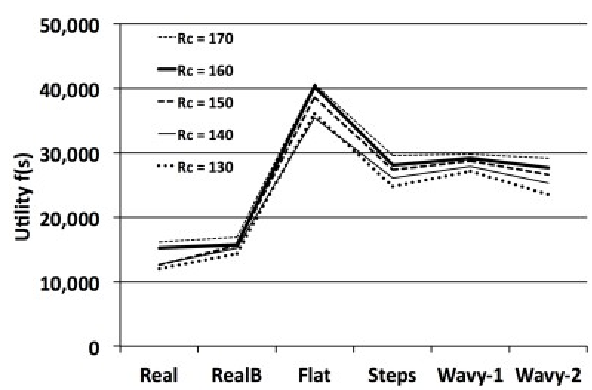

Figure 3: Original results from the 2.5D Terrain Experiment.

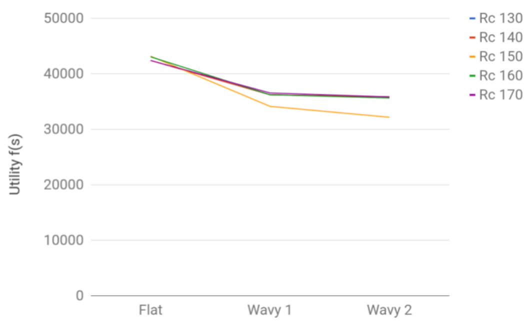

Figure 4: Reproduced results using Popper.

the values in Figure 5 are higher than the values in Figure 4. This difference is because the original paper used a custom, synchronous simulator that was programmed in C++. Since then, the author of the experiment decided to switch environments. For this reason, the experiment has been translated into a Cooja environment as a new Java model in the event-driven simulator. Despite missing elements, due to the author's decision, the trend in both Figure 4 and Figure 5 is uniform.

4 CONTROLLED AND REAL-WORLD EXPERIMENTS

In this section we briefly describe two Popper pipelines showcasing network experiments on testbeds and in real-world scenarios. These can be found in the repository corresponding to this paper. Our goal is to provide pipelines that can serve as the starting point for experimenters that are working on these networks research subdomains.

4.1 Experiments on Testbeds

Multiple testbeds are available. In our case, we make use of the NSF-sponsored GENI federation of datacenters in the US. This infrastructure provides with a wide variety of compute, storage and networking hardware, including traditional, IoT and city-scale wireless devices. The most time-consuming stages of a pipeline involving the use of a testbed are (1) the setup stage, where resources are allocated; and (2) the experiment "orchestration" phase, where the logic of the experiment is executed. The pipeline we have implemented makes use of Geni-lib and Ansible to accomplish these two tasks. These two automation frameworks are generic and allow the execution of arbitrary network topologies, as well as the execution of benchmarks and protocol tests.

4.2 Real-world Measurements

The real world is complex, and capturing measurements helps understand researchers to make sense out of all this complexity. This type of studies usually involves the deployment of nodes that test intra- and inter-domain features such as internet protocol performance. One of the most important aspects of this type of experiments is the collection of contextual information that might help readers and reviewers to interpret and verify the claims. Information such as which service provider is being used, physical location of endpoints, type of networks being used, among others. The pipeline we have implemented deploys a client-server setup, runs tests and captures all this information automatically.

5 LESSONS LEARNED

Recent studies have identified good practices that can (and should) be followed in order to ease the re-execution of published networking experiments [11]. In addition to these, coming from a practical angle, we identify the following:

1. *Reproducibility as a first-class issue.* One of the main takeaways that we learned is the difficulty involved in automating an experiment that was not implemented with reproducibility in mind. In our case, we had the opportunity to closely work with the original authors of the network experiments. However, having access to the original authors is quite uncommon. Even with the opportunity of consulting with the authors, reproducing their experiment was an extensive task as they have made a few changes to their work since publication. This further shows how focusing on reproducibility from the start (e.g., using the Popper convention or other reproducibility tools) makes it easier to obtain a versioned, automated, and portable pipeline that others can easily re-execute. This finding, among others related to Popper best practices have been documented in [12].
2. *Use a workflow automation tool.* Compared to workflows specified in scientific workflow engines such as Taverna or Pegasus, Popper workflows are relatively simple. One could describe Popper workflows as the highest-level workflow of a scientific exploration, which users or automation services interact with. Other alternative tools that can be used for this are CWL, Yadage, CK, among others.
3. *Make experiments self-contained.* Automating an experiment does not necessarily result in creating self-contained experiments. A useful check for verifying whether an experiment is self-contained is to start from a clean-slate environment (e.g. a base OS Docker image), clone the repository that holds the pipeline, and run it. If something fails, then the experiment is not self-contained.
4. *Expose relevant experiment parameters.* Once an experiment is successfully re-executed, the likely next step of a reviewer and readers is to ask "what-if" types of questions. For example, "what if I modified the number of nodes in the system?" or "what if I modified the amount of memory available to the experiment?". In order to make it easier for consumers of published research to "play" with experiments, researchers can expose in plain text format (e.g. a YAML file in the folder where the pipeline is stored) that clearly exposes the parameters that the experiment is sensible to.
5. *Capture relevant information for post-mortem analysis.* When an experiment fails, the first question we ask ourselves is: "what has changed, between my re-execution and the previous successful reproduction of results?". In order to make it easier for others to answer this question, we should attempt,

on a best-effort basis, to collect as much contextual information as possible so that it can be leveraged by others (or ourselves) to apply this type of root cause analysis.

6 CONCLUSION

Experimental reproducibility is an essential component of scientific research. However, unlike other disciplines in the sciences, reproducing experimental results in the field of computer science and engineering has not been part of common practice for a number of reasons. This includes the fact that it is a fast evolving field and re-creating the original experimental environment from the ground up is often too complex and sometimes impossible. In this paper, we reported our experience using a recently proposed tool called Popper which employs a systematic approach to automating the experimental process, including experimental setup, (re-)execution, data analysis, and visualization. We showcase how Popper can be used to facilitate experimental reproducibility in the experimental computer networking domain. We hope our work will provide a workflow template to guide network researchers and practitioners towards making experimental reproducibility part of the best practices in the field.

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