

# Quality Control Methodology for Simulation Models of Computer Network Protocols

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## Abstract

This paper summarizes know-how about modeling and simulation of computer networking protocols we contributed to the OMNeT++ community. We propose a methodology aiming to set a reliable ground truth for the quality of simulation models of networking protocols. We demonstrate the application of this methodology on our EIGRP source code pull-requested to the INET framework.

## 1 Introduction

The quality of simulation results depends on the accuracy of used models, namely, on how precisely models reflect the behavior of the real-world system. In computer science, developing a proper model and subsequent employment of this model in the running simulation is about finding a balance between complexity and effectiveness. Model implementation should be accompanied by reproducible proof to show how verification and validation (V&V) was done. Thanks to that, other programmers can assess the accuracy of the model and its feasibility in the frame of different scenarios.

IEEE 1012 [14] standard defines V&V as processes, which determine whether developed products of a given activity conform to the requirements of that activity and whether the software satisfies its intended use and user needs. V&V processes should provide an objective assessment of software products, namely, demonstrate software correctness, completeness, accuracy, consistency, and testability. IEEE standard, of course, tries to accommodate whatever type of software engineering effort, while we will apply its core principles in the field of computer modeling and simulation.

The domain of computer network protocols is our primary research and teaching interest. We are periodic contributors of simulation models for the OMNeT++ ecosystem. This paper focuses on our experience with the testing of developed models and their comparison with referential implementations. Our goal is to define and demonstrate the methodology that is helping us to produce precise simulation models.

This paper has the following structure. Section 2 elaborates on inputs of the simulation model development process. Section 3 describes the proposed methodology on how to validate, verify and test simulation models; moreover, this section discusses certain challenges and introduces useful practices. Section 4 demonstrates methodology on the use-case of EIGRP models for OMNeT++ and its framework INET. The paper is concluded in Section 5.

## 2 State of the Art

The following subsections present different ways of formal description of network protocols, highlight completely different approaches by their authors in their design and unravel general best practices of the V&V process. We provide a short overview of the most commonly used referential implementations by the networking community at the end of this section.

## 2.1 Protocol Definition

Any layered model (e.g., ISO/OSI, TCP/IP, RINA [23]) of computer network slices its functionality onto a set of collaborating protocols. Many computer protocols exist to handle different use-cases due to each protocol's unique functionality within the fixed scope (i.e., layer). Basically, all computer networking protocols are defined by the rules of communication, which specify syntax, semantics, and timing of messages. These rules can be formally described either using deterministic finite-state machines (FSM) or temporal logic.

Theory and understanding of FSMs are less comprehensive and more accessible to programmers than temporal logic. Therefore, computer network protocol modeling means conversion of protocol rules onto FSM, where 1) *FSM states* represent internal communication statuses; and 2) *FSM transitions* are a set of actions initiated by messages/events. FSM as a protocol model is then implemented using means (i.e., languages, built-in tools) available for the selected domain.

It depends on the domain if means for behavior/state description and message syntax definition are different or the same. For instance in OMNeT++, we use C++ (\*.cc/\*.h files) to implement behavior, NED language (\*.ned files) to layout composition, and message definitions (\*.msg files) for syntax. In the case of network stack within the operating system (OS), most data-link, network and transport layer protocols (including their messages) are implemented via C/C++. For message definition purposes, there even exist (semi)automated approaches that will help with the conversion of protocol specification into source code such as ASN.1<sup>1</sup> or Google Protocol Buffer<sup>2</sup>.

## 2.2 Referential Implementations

Standards – such as RFCs, or IEEE 802 series – outline all mandatory protocol rules so that different implementations are compatible with each other. Nevertheless, some standards allow or even encourage the flexibility of implementation. For instance:

- IPv6 is using Extension Headers to add functionality that is not present in the Fixed Header. New Extension Headers handling unique use-cases can be created based on predefined rules and recommendations [8] (section 4, pages 7 – 25). Even the structure of already defined Extension Headers can be the subject of discussion, where different parties would implement it according to their needs (e.g., [18]).
- Similarly to that IS-IS, EIGRP [22] (section 6.6, pages 51 – 52), TCP [17] (section 3.1, pages 17 – 19), and others are often using the concept of type-length-value (TLV) fields to support easy updates of protocol functionality without the need to standardize a new version as is the case with OSPF for example.

The examples provided above show that the standard itself is not the ultimate source of protocol definition because actual implementations can also contribute to overall protocol functionality. Therefore, the V&V process should include the comparison of the simulation model with another implementation of the selected protocol. Choosing the referential implementation has a significant impact because messages and results generated by this reference affect the development process of the simulation model. It would be wise to compare the simulation model with multiple referential implementations in order to obtain an objective and comprehensive

<sup>1</sup>ASN.1 is codified in the standard available at <https://www.itu.int/rec/T-REC-X.680-201508-I/en>

<sup>2</sup>Interface description language including code generator is available in the following GitHub repository <https://github.com/protocolbuffers/protobuf>

evaluation. However, this may be in contradiction with the availability of resources (e.g., time, hardware) to the programmer. So if just a single referential implementation is used, let it be the one closest to the simulated phenomenon.

In our opinion, the best practice for referential implementation is to use an active network device (like a router or a switch) from a well-known vendor. In that case, we have a chance to test multiple referential implementations on the same device thanks to generally available firmware updates. Moreover, employers of well-known vendors often co-create (or at least actively participate in discussions) during the standard development, which makes vendor implementations more trustworthy regarding compliance.

Here is a short non-exclusive list of referential implementations we have seen being used with respect to INET contributions:

- **Cisco Packet Tracer** [7]: It is a tool associated with the Cisco NetAcad; it is used as a learning environment supporting the teaching of the curriculum of various computer networking classes. Diving deeper into details, Cisco Packet Tracer is a discrete event simulator containing models mimicking the behavior of selected products (mostly small office/home office routers, switches, access points, and security appliances) from the Cisco portfolio. Simulation models features have significant differences between different Cisco Packet Tracer versions. Based on version changelogs [6], community observations, and our insight, Cisco Packet Tracer embeds only limited equipment features. The majority of supported protocols are simplified or altered in behavior or message structure.
- **Physical device**: If possible, then the physical device with operating systems tailored for computer networking is the best referential implementation one can have. However, specific protocols might be purposely constrained or not available to align with the business missions of such devices. On the one hand, open standard TRILL protocol is often omitted at the expense of similar yet proprietary protocols (e.g., FabricPath). On the other hand, originally proprietary protocol EIGRP was released to the public domain, but other vendors simply ignore it. Another cavity of employing physical devices is the cost because it may be expensive to build analogous topology to the simulated scenario.
- **GNS3** [13], **EVE-ng** [19]: GNS3 and EVE-ng are emulators of active network devices. They can unpack and run binary firmware images (e.g., Cisco IOS files, QEMU images) of these devices in virtualized environments. This means that protocol implementation on the virtualized device is the same as on the real one. GNS3 and EVE-ng employ the same virtualization (either QEMU [4] or Dynamips [10]), but they differ only in the end-user interface; while GNS3 requires a dedicated application installed, EVE-ng wraps its functionality in the form of a web application. Using both GNS3 or EVE-ng, the programmer may easily create complex topologies running tens even hundreds of nodes (the only limitation is available CPU and memory on the hosting computer) running reliable physical device implementation for nearly zero cost.

We consider Cisco Packet Tracer as an inferior choice for referential implementation due to its limitations. The physical device is always the best option when it comes to accuracy to real-life protocol behavior. However, it is bold to expect that other programmers who want to repeat the V&V process would possess exactly the same number of devices with the same peripheral configurations and firmware versions. We prefer to use the emulators mentioned above because their implementation is identical to physical devices. Moreover, V&V process reproduction is more effortless because both these tools offer convenient exports of topologies (including their running configuration and other state properties), which can be easily attached or referenced in the repositories of simulation models.

## 3 Quality Control

This paper aims to define a structured V&V process that any programmer may use as a cookbook for quality control of simulation models. This section briefly informs about various challenges which may be encountered during the development and testing phases. Then it describes each step of methodology based on all previously mentioned observations in this article.

### 3.1 Challenges

Here goes a curated and non-definitive list of challenges impacting development. We provide our personal view on dealing with these challenges and welcome any counter-opinions.

#### 3.1.1 Level of Accuracy

A complete conversion of all protocol rules may lead to extremely complicated FSM (with many states/transitions and complex message variants). The situation gets even more tricky with protocols that offload signalization or data transfer onto other protocols – e.g., IPsec ESP/AH cooperating with ISAKMP, RTCP/RTP cooperating with H.323/SIP.

There are approaches and complete tools capable of FSM minimization that would remove unnecessary states or transitions. However, this type of optimization was most probably already done by authors during the protocol design. The only other option for reducing complex FSM is to purposely omit a subset of protocol features. This means a decrease in the accuracy of the simulation model. There is no rule of thumb for what to include and exclude because it depends on the programmer’s goals. Nevertheless, the following section might be helpful when questioning the desired level of accuracy of implemented computer network protocol.

#### 3.1.2 Application of Cryptography

Cryptography is being used in the protocol design to guarantee confidentiality (no one except sender and receiver can understand the message), integrity (any tempering with the message is recognized by the receiver), and authenticity (identity of single or both parties of the communication are guaranteed). The programmer needs to decide whether or not to include cryptography in the simulation model.

There are two main arguments for why to do it: 1) the messages generated by the simulator would be the same as messages produced by referential simulation; thus 2) it is the only way how to also support hardware in the loop (HIL) simulation. The following list represents counter-arguments why not add cryptography: 1) there is no reason why to support cryptography primitives in deterministic simulation scenarios – it is a known fact before running the simulation whether confidentiality/integrity/authenticity is guaranteed or not between involved parties; 2) the boilerplate of the simulation model source code tends to increase dramatically by adding external libraries handling cryptography (such as OpenSSL [11]); which leads to 3) cryptography poses an overhead on resources (mainly CPU time and memory) when running the simulation, which means we need to wait longer for results or we could be even unable to simulate complex topologies with cryptography enabled.

Since we have never considered HIL simulations as the use-case for our models, we skip real-life implementation of the cryptography primitives. To achieve a comparable message structure, we replace relevant fields within the protocol message with an appropriate magic string. The magic string can be used as piggybacking mechanism for the receiver that the message “is encrypted/authenticated” or “with intact integrity”.

### 3.1.3 Timing

Time is of the essence when comparing protocol messages' confluence between devices running referential implementation and simulation models. Referential implementation of the protocol runs in real-time, while the simulation is governed by a discrete event scheduler (for OMNeT++ see [21], sections 417.6).

Due to the lack of global clocks, it is hard to measure durations, trigger actions, and control events between devices in real-time. Therefore, it is absolutely mandatory to employ time synchronization protocols like NTP [20] or PTP [15] for devices running referential implementation. NTP aims to achieve millisecond-level, while PTP guarantees up to nanosecond-level synchronization accuracy. Therefore, PTP is always a better choice; unfortunately, most active network devices support only NTP. If and only if the clocks are synchronized, the programmer is able to produce reliable baselines in the topologies running referential implementations.

Every discrete event simulator has built-in mechanisms to schedule events and trigger them during the simulation run. In the case of the INET framework, `ScenarioManager` [16] offers setting up and control over simulation via scripted execution of events defined in the XML file (see for example Figure 1).

Scheduling the event in the environment running referential implementation is more complicated (whether the device is real or virtualized). It depends on the vendor, what scripting options are available. For instance, operating systems of many Cisco devices offer Embedded Event Manager (EEM) [12] (the configuration snippet disabling specific interface at the given moment is depicted in Figure 2) or TCL [5]. Instead of preloaded scripts, the programmer may use a more centralized approach (e.g., Expect [9], Ansible [3]). Scripts are present on a single machine that would connect remotely (using SSH, Telnet, HTTP) to the device at the right moment. Scripts would then be executed through a remote connection. In the case of time-driven scripts, this approach offers more robustness since there is only a single clock controlling execution and better visibility for the scheduling of event batches.

### 3.1.4 Control Plane Randomness

The control plane of the actual device runs many different processes, where each is responsible for a different protocol or functionality. The control plane dynamically switches between these processes based on OS resource schedulers. This context switching introduces a degree of randomness, which impacts the reproducibility and baselines' readability. Following symptoms relate to this challenge:

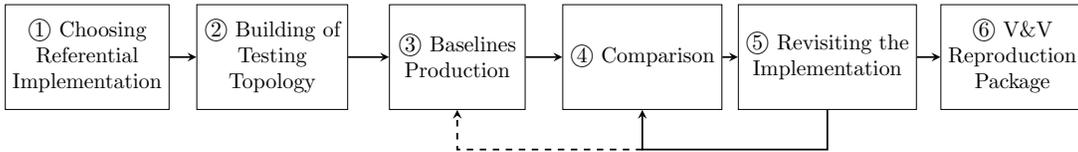
- Stochastic delays are observed in the functionality of referential implementation when the control plane is preoccupied with another process;
- Consecutive protocol messages have non-standard gaps between each other due to the packet pacing. This jitter between messages is purposely introduced by the control plane either to avoid potential racing conditions between protocol instances or to guarantee stable bandwidth consumption.

Any simulation model cannot accurately abstract above mentioned symptoms. Hence, they cannot be replicated inside the simulation. This means that any comparison between referential implementation and its simulated variant should consider the factor of the control plane randomness.

### 3.2 Methodology

At least any V&V process is a natural part of any software engineering effort. We are sure that every programmer is conducting it in the form of source code testing. In this section, we are not codifying anything new for the OMNeT++ community. We just want to articulate quality control methodology related to the development of simulation models, including best practices based on the previous elaboration of our thoughts.

The proposed methodology consists of six consecutive phases depicted in the following diagram and described below:



- ① **Choosing Referential Implementation:** The initial phase is about choosing the proper referential implementation compatible with expected simulation goals. As stated in section 2.2, we recommend either physical devices from a trusted vendor or a network emulator with a corresponding firmware image.
- ② **Building of Testing Topology:** Before employing a developed simulation model in the large-scale simulation, it is crucial to successfully conduct V&V on the smallest possible topology, which would offer a good testing ground to assess normal behavior and treatment of edge cases. It is important to keep parameters (e.g., interface speeds, IP subnetting, number of adjacent devices, protocol-specific configuration) constant across real and simulated topology to maintain integrity.
- ③ **Baselines Production:** We predominantly use the following three types of baselines produced by referential implementation: a) Syslog messages that include information about overall control-plane status; b) outputs of `show/debug` commands that describe in detail operation of referential implementation; c) PCAP files that contain computer traffic dumps. While Syslog and `show/debug` outputs are specific for a single device; PCAP files offer a view on protocol context between multiple devices since capture contains data from both directions (i.e., incoming/outgoing to/from selected interface). All above-mentioned baselines need to include time information which is important for subsequent comparison with the corresponding simulation scenario. The accuracy for all baseline types can be potentially enhanced up to nanosecond precision.
- ④ **Comparison:** Whenever a developed simulation model is ready, it is being tested in preferably different simulation topologies and various scenarios. All of these test runs produce results (such as console message, trace, or PCAP) that are inputs for comparison. The rest of this phase is about objective assessment between referential implementation and simulation model is made. We recognize two levels of such comparison: *protocol level*, where we are focusing on the generated messages and their integrity (both syntactical and semantical); and *abstract data structure level*, which focuses on states of abstract data structures used by the protocol, such as the routing table, interface table, CAM table, topology table for EIGRP, link-state database for OSPF, etc. Needless to say that a combination of both levels achieves the most objective evaluation. Thanks to the impact of discussed challenges, differences of various magnitude can be encountered during the comparison. Hence, it is important to conduct baselines production and comparison

- repeatedly. There is a very thin line between making the objective comparison of ground-truth baseline and simulated behavior, and subjectively choosing matching simulation results onto the corresponding baseline.
- ⑤ **Revisiting the Implementation:** The simulation model can be modified, updated, or even completely redesigned depending on findings from the previous step. After all the changes are introduced to the implementation, it is wise to revert back to phases ④ or ⑤, to verify the validity of changes. This process is repeated until the quality of the simulation model is sufficient (hopefully, the quality would even exceed original expectations).
  - ⑥ **V&V Reproduction Package:** This phase is a memo that result reproduction is essential. Any contributed simulation model should be accompanied by materials (e.g., referential implementation version, baselines including PCAP/Syslog dumps, simulation trace files) that allow reproduction of resulting behavior as proclaimed by the author. Additional testing and V&V done by the community have a chance to find new errors or unhandled cases that may further improve the quality of resulting simulation models.

## 4 Demonstration

This section contains a demonstration of the V&V methodology proposed in Section 3. We decided to demonstrate this process on INET's EIGRP simulation model as available in INET 4.3 running in OMNeT++ 6.0 pre10. The simulation model is configured via a combination of `Ipv4NetworkConfigurator` for assigning IP addresses and EIGRP specific `.xml` file which has a deliberately similar structure to Cisco configuration.

### 4.1 Choosing Referential Implementation

Currently, the only viable choice for referential implementation of EIGRP is Cisco. Firstly, Cisco Systems is the author of this protocol. As such, there should be the smallest amount of discrepancies between the RFC and actual implementation caused by genuine errors and mistakes in the implementation. Secondly, there are very few other implementations that could be used as a reference. However, some chapters (e.g. stub routing) are still completely missing in RFC 7868 [22] even though they are fully operational on Cisco devices. Therefore, we are using network emulator EVE-ng with IOS version *15.7(3)M2* to build our referential topology.

### 4.2 Building of Testing Topology

We decided to use the topology shown in Figure 3. It consists of three routers connected to each other via 10 Mbps Ethernet links. EIGRP is configured on all routers and enabled on all interfaces. Additionally, each router has its own LAN which is advertised by the EIGRP process. This demonstration considers two scenarios (with identical configuration).

- **Scenario I: Initial Route Discovery:** The first scenario focuses on the neighbor discovery, adjacency establishment, and initial routing information exchange process. These are typical activities when a new router/link is introduced to the topology. In this scenario, a link between routers R1 and R2 is added. This link is highlighted green in the Figure 3. When this link is introduced, all routers are already configured for EIGRP and R1 and R3, as well as R3 and R2, are already neighbors and have exchanged routing information.

The addition of this link is the starting event for the measurements. Scenario investigates traffic between R1 and R2 and R1's routing table.

- **Scenario II: Topology Change Propagation:** The second scenario focuses on route selection and propagation of change in the topology. In this scenario, a link between R1 and R2, previously introduced to the topology in Scenario I, is removed from the topology after the topology has reached convergence. The disconnected link is highlighted green in the Figure 3 and the removal of this link is the starting event for the measurements. This scenario focuses on the traffic between R1 and R3 and R1's routing table. The result is expected to be influenced by the race condition as both R1 and R2 will try to advertise this change in the topology to R3 as soon as possible.

### 4.3 Baseline Production

Because EVE-ng handles clock synchronization automatically, we just prepared tailored Cisco EEM applets to execute previously mentioned scenarios on the referential topology. EVE-ng is capable to dump traffic on selected interfaces into `.pcap` file that can be analyzed. Wireshark view for the captured traffic on the referential topology is shown in Figures 4 and 10.

We prepared appropriate XML files for `ScenarioManager`, which manages intended scenarios for a simulation. Traffic generated by simulation models can be viewed in the *Message/packet traffic* window, and each message can be individually inspected. Some simulation models even offer export to PCAP, but this is not true for our EIGRP model as of this moment. Captured traffic in the simulation is shown in Figures 5 and 11.

### 4.4 Comparison: Protocol Level

For this particular comparison, we focus on messages' *format, content, order* and *context*. While format can be checked by a simple comparison of messages of the same type, content, order, and context are harder to compare as it requires a good understanding of the protocol.

The overall packet length can be misleading (at least for this case). There are genuine implementation differences, e.g., the EIGRP simulation model advertises **Stub routing information** in every *EIGRP Hello* message while Cisco includes **Software Version** and **Peer Topology ID List**. Because aspects like messages' content and order on the referential topology can be affected by the control plane randomness, it is generally beneficial to conduct multiple measurements and closely analyze the one most compatible with the simulation.

#### 4.4.1 Scenario I

Captured traffic between routers R1 and R2 is shown in Figures 4 and 5. This traffic is compared to each other and most corresponding messages are aligned to the same row in Table 1. A closer inspection of messages is shown in Figures 6 and 7. The referential topology produces very consistent results in this scenario with the race condition causing only marginal differences between measurements. This makes the comparison rather straightforward.

#### 4.4.2 Scenario II

Captured traffic between routers R1 and R3 is shown in Figures 10 and 11. This traffic is compared and most corresponding messages are put on the same row in Table 2. A closer inspection of an *EIGRP Query* is shown in Figures 12. The result on the referential topology

is affected by the race condition which caused the disconnected route 10.0.12.0/30 to become unreachable on router R1 at the very end instead of on the first received *EIGRP Reply*.

#### 4.4.3 Results

Even though all messages were contextually correct, the simulation model is not perfect in this regard. The first scenario shows multiple message format errors in TLVs. Another deviation from the referential implementation the model exhibited is the unnecessary use of unicast during the initial synchronization. The second scenario shows an error that causes a route with multiple successors to change into the Active state when one of these successors is lost, which leads to unnecessary traffic. Overall, traffic patterns are easily recognizable and the simulation models still exchanged all of the key information needed for correct changes in data structures like routing or topology table.

### 4.5 Comparison: Routing Table Level

This comparison focuses on changes to the abstract data structures such as routing table, EIGRP topology, or neighbor tables which all can be used to assess the behavior of the simulation model. The snapshot of each of these tables is recorded at the beginning and at the end of the scenario. After the measurement, we perform simple side-by-side comparison while concerning namely: *route source* (identifies how the route was learned, EIGRP labels it with the letter D); *destination* (identifies destination network and mask); *metric* (identifies a value assigned to reach the destination network); *next-hop* (identifies the address of next router); *exit-interface* (identifies the outgoing interface).

Because the configuration is identical between the referential topology and the simulation, all of the above-mentioned fields should be the exact same.

#### 4.5.1 Scenario I

Figure 8 depicts the comparison of initial states of the R1's routing table. Destination 10.0.12.0/30 is not available at this point in either case. After the new link between routers R1 and R2 is established, it takes only a few seconds for R1 to make necessary changes to the routing table. Figure 9 shows the state of R1's routing table after the topology has reached convergence in both cases.

#### 4.5.2 Scenario II

The initial state for this scenario is the same as the final state from the first scenario (i.e., 9). The final state of the routing tables for this scenario is shown in Figure 13. All measured metrics are as expected.

#### 4.5.3 Results

In both scenarios, there was no difference in any EIGRP routing table entry between the simulation and the referential configuration.

### 4.6 Revisiting the Implementation

With this new information about the quality of the model, the programmer is able to proceed with fixing each individual error. While errors like the ones found in Scenario I are easy to fix,

as they are mostly just badly predefined numerical values, errors in the FSM like the one found in Scenario II can be much more complex. It is crucial to repeat the previous step in the V&V process after the changes are introduced to the model.

#### 4.7 V&V Reproduction Package

All necessary files needed to reproduce our experiments are published on [1]. Results from our measurements are also included.

### 5 Conclusion

In this paper, we have mentioned factors impacting the development of simulation models. We have outlined challenges and provided lessons learned for the V&V process, primarily for the domain of computer network protocols. The main contribution of this paper is the transparent methodology that constitutes several phases aiming at improving the overall quality of the resulting simulation model. We demonstrated this methodology on the use-case of our recent contribution [2] to INET, which involves full-fledged support of the EIGRP routing protocol. We hope this paper will stimulate discussion within the OMNeT++ community (and hopefully beyond it), which would help find a common agreement on the V&V process for any contributions.

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## A Configuration Snippets

```
<scenario>
  <at t="50">
    <disconnect src-module="R1" src-gate="ethg[0]" />
  </at>
  <at t="100">
    <connect src-module="R2" src-gate="ethg[0]" dest-module="R1"
      dest-gate="ethg[0]" channel-type="inet.node.ethernet.Eth10M" />
  </at>
</scenario>
```

Figure 1: The configuration of ScenarioManager for demonstration from Section 4 which disconnects and reconnects the link between routers R1 and R2 at 50 and 100 seconds of simulation time respectively.

```
R(config)# event manager applet SHUTDOWN-APPLET
R(config-applet)# event timer cron cron-entry "30 15 * * *"
R(config-applet)# action 1.0 cli command "enable"
R(config-applet)# action 2.0 cli command "configure terminal"
R(config-applet)# action 3.0 cli command "interface ethernet 0/0"
R(config-applet)# action 4.0 cli command "shutdown"
R(config-applet)# action 5.0 cli command "end"
R(config-applet)# action 6.0 syslog msg "Applet executed."
```

Figure 2: Cisco EEM Applet which executes `shutdown` command on interface `ethernet 0/0` at a given time according to the router's clock, `15:30` in this case.

## B Testing topology

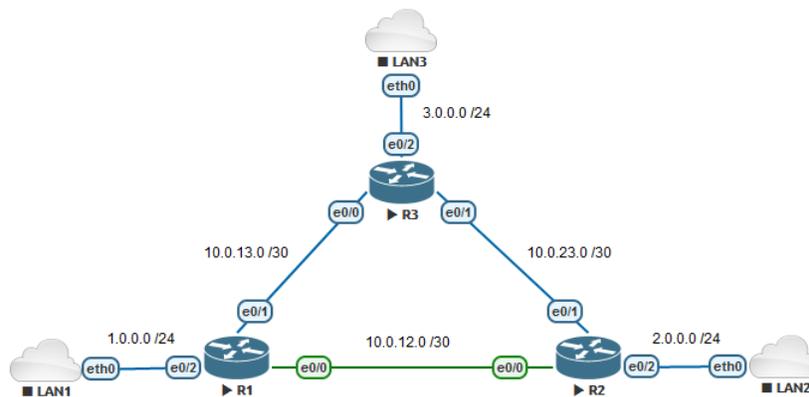


Figure 3: EIGRP testing topology. Scenarios are executed by manipulation of link highlighted in green.

### C Comparison: Scenario I - Initial Route Discovery

No.	Time	Source	Destination	Protocol	Length	Info
1	3.729698	10.0.12.1	224.0.0.10	EIGRP	84	Hello
2	3.738674	10.0.12.2	224.0.0.10	EIGRP	84	Hello
3	3.739372	10.0.12.2	10.0.12.1	EIGRP	60	Update
4	5.745241	10.0.12.2	10.0.12.1	EIGRP	60	Update
5	5.745326	10.0.12.1	10.0.12.2	EIGRP	60	Update
6	5.753815	10.0.12.2	224.0.0.10	EIGRP	276	Update
7	5.753882	10.0.12.2	10.0.12.1	EIGRP	60	Hello (Ack)
8	5.766658	10.0.12.1	224.0.0.10	EIGRP	276	Update
9	5.766981	10.0.12.2	10.0.12.1	EIGRP	60	Hello (Ack)
10	8.758402	10.0.12.2	10.0.12.1	EIGRP	187	Update
11	8.767811	10.0.12.1	10.0.12.2	EIGRP	60	Hello (Ack)
12	8.776812	10.0.12.2	224.0.0.10	EIGRP	143	Update
13	8.777383	10.0.12.1	224.0.0.10	EIGRP	143	Update
14	8.777768	10.0.12.2	10.0.12.1	EIGRP	60	Hello (Ack)
15	8.778087	10.0.12.1	10.0.12.2	EIGRP	60	Hello (Ack)

Figure 4: Scenario I - Captured EIGRP traffic between R1 and R2 displayed with Wireshark

#	Time	Relevant Hops	Name	ID / Source	Destination	Type	Length
1	54.500 072	R1 --> R2	EIGRP_HELLO_MSG	10.0.12.1	224.0.0.10	EIGRP	78 B
2	54.500 072	R2 --> R1	EIGRP_HELLO_MSG	10.0.12.2	224.0.0.10	EIGRP	78 B
3	54.500 144	R1 --> R2	EIGRP_UPDATE_MSG	10.0.12.1	10.0.12.2	EIGRP	72 B
4	54.500 144	R2 --> R1	EIGRP_UPDATE_MSG	10.0.12.2	10.0.12.1	EIGRP	72 B
5	54.500 211 200	R1 --> R2	EIGRP_ACK_MSG	10.0.12.1	10.0.12.2	EIGRP	72 B
6	54.500 211 200	R2 --> R1	EIGRP_ACK_MSG	10.0.12.2	10.0.12.1	EIGRP	72 B
7	54.500 278 400	R1 --> R2	EIGRP_UPDATE_MSG	10.0.12.1	10.0.12.2	EIGRP	286 B
8	54.500 278 400	R2 --> R1	EIGRP_UPDATE_MSG	10.0.12.2	10.0.12.1	EIGRP	286 B
9	54.500 516 800	R1 --> R2	EIGRP_ACK_MSG	10.0.12.1	10.0.12.2	EIGRP	72 B
10	54.500 516 800	R2 --> R1	EIGRP_ACK_MSG	10.0.12.2	10.0.12.1	EIGRP	72 B
11	54.500 584	R1 --> R2	EIGRP_UPDATE_MSG	10.0.12.1	224.0.0.10	EIGRP	154 B
12	54.500 584	R2 --> R1	EIGRP_UPDATE_MSG	10.0.12.2	224.0.0.10	EIGRP	154 B
13	54.500 716 800	R1 --> R2	EIGRP_ACK_MSG	10.0.12.1	10.0.12.2	EIGRP	72 B
14	54.500 716 800	R2 --> R1	EIGRP_ACK_MSG	10.0.12.2	10.0.12.1	EIGRP	72 B

Figure 5: Scenario I - Captured EIGRP traffic between R1 and R2 displayed in OMNeT++

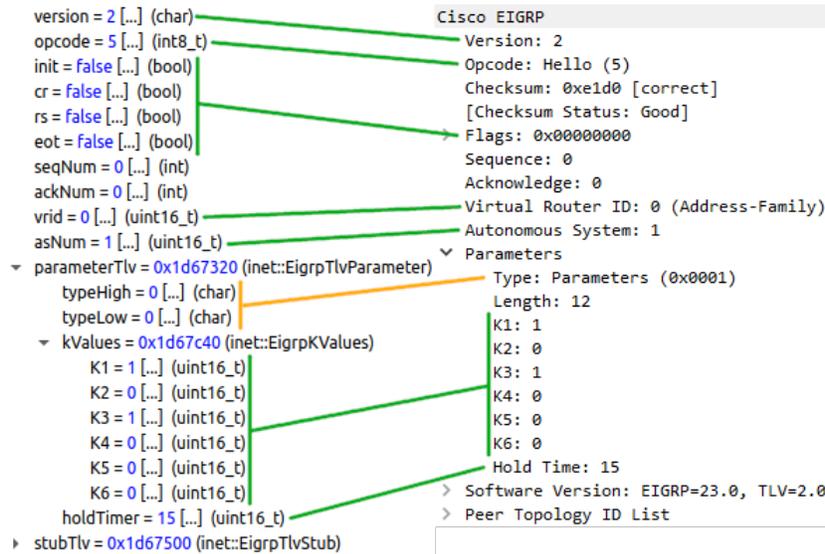


Figure 6: Scenario I - Comparison of Hello messages between referential topology and OM-NeT++ simulation.

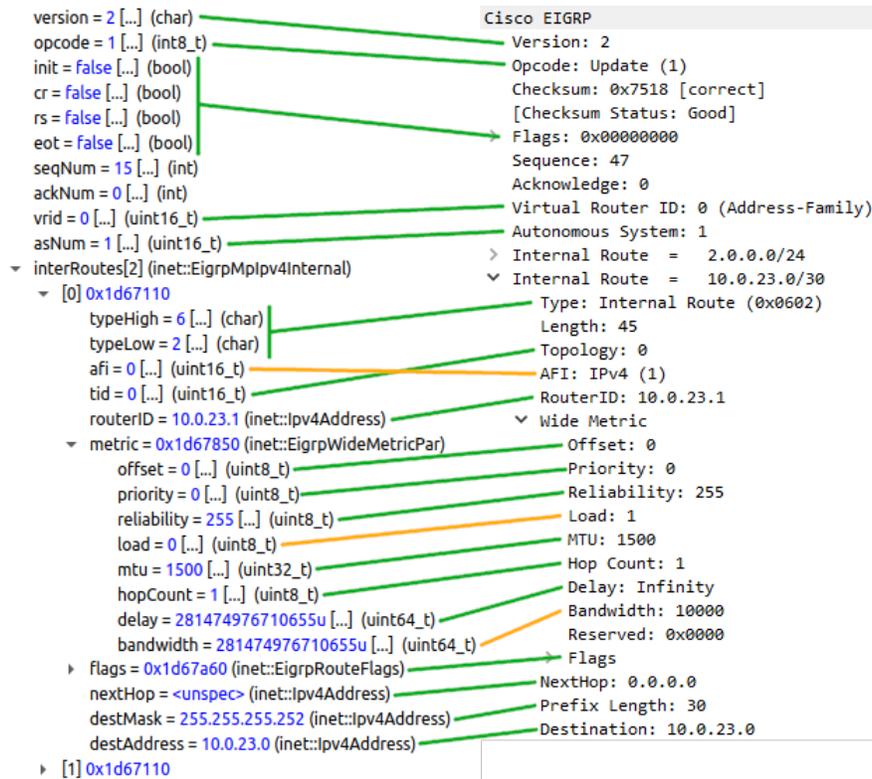


Figure 7: Scenario I - Comparison of Update message 13 from referential topology and Update message 11 from the OMNeT++ simulation.

Cisco	OMNeT++	Description
1, 2	1, 2	Exchange of Hello packets. When a router receives a Hello message from a new neighbor, it creates a new entry for this specific neighbor and sets its status to <b>pending</b> . The content and format of these messages are shown in Figure 6.
3, 4, 5	3, 4	Exchange of Update packets with INIT flag. These do not contain any routing information. On the referential topology router R1 did not acknowledge message 3 in time, so router R2 re-sent the Update as message 4, message 5 contains piggybacked acknowledgement for this message.
6	-	This Update message contains advertised routes from router R2 and only appears on the referential topology. This message is sent because the neighbor status from R2's point of view went from <b>pending</b> to <b>up</b> . This causes the message to be ignored and not acknowledged by router R1 because from its point of view, R2's neighbor status is still pending as R1 did not receive an acknowledgment for its initial update message, message 5, yet.
7	5, 6	Acknowledgments for initial Update messages. There is only one acknowledgment on the referential topology because it was piggybacked into the Update message as previously mentioned.
8, 10	7, 8	Exchange of Update messages containing all advertised routes by both routers. On the referential topology, one Update is sent as unicast because it is a retransmission of message 6. It is also smaller because the router applied the <i>split-horizon</i> rule which prohibits an advertisement of a route towards its next hop. Another Update on the referential topology is sent as multicast. This is in contrast to the simulation model which uses unicast for the Update messages during the initial synchronization.
9, 11	9, 10	Acknowledgements for Update messages.
12, 13	11, 12	Exchange of Update messages advertising networks which have a successor on this interface as unreachable, i.e, 2.0.0.0/24 and 10.0.23.0/30 by R1 and 1.0.0.0/24 and 10.0.13.0/30 by R2. This is according to the <i>poison reverse</i> rule. The content and format of these messages is shown in Figure 7.
14, 15	13, 14	Acknowledgments for Update messages.

Table 1: Scenario I - Analysis of the traffic between routers R1 and R2.

```

1.0.0.0/8 is variably subnetted, 2 subnets, 2 masks
C 1.0.0.0/24 is directly connected, Ethernet0/2
L 1.0.0.1/32 is directly connected, Ethernet0/2
D 2.0.0.0/24 is subnetted, 1 subnets
D 2.0.0.0 [90/332800] via 10.0.13.2, 00:01:27, Ethernet0/1
D 3.0.0.0/24 is subnetted, 1 subnets
D 3.0.0.0 [90/307200] via 10.0.13.2, 00:01:44, Ethernet0/1
C 10.0.0.0/8 is variably subnetted, 3 subnets, 2 masks
C 10.0.13.0/30 is directly connected, Ethernet0/1
L 10.0.13.1/32 is directly connected, Ethernet0/1
D 10.0.23.0/30 [90/307200] via 10.0.13.2, 00:01:44, Ethernet0/1

elements[6] (inet:ipv4Route *)
[0] C 10.0.13.0/30 gw:* metric:200 if:eth1
[1] D 10.0.23.0/30 gw:10.0.13.2 metric:307200 if:eth1
[2] C 1.0.0.0/24 gw:* metric:200 if:eth2
[3] D 2.0.0.0/24 gw:10.0.13.2 metric:332800 if:eth1
[4] D 3.0.0.0/24 gw:10.0.13.2 metric:307200 if:eth1
[5] C 127.0.0.0/8 gw:* metric:1 if:lo0

```

Figure 8: Scenario I - Comparison of router R1's routing table in its initial state.

```

1.0.0.0/8 is variably subnetted, 2 subnets, 2 masks
C 1.0.0.0/24 is directly connected, Ethernet0/2
L 1.0.0.1/32 is directly connected, Ethernet0/2
D 2.0.0.0/24 is subnetted, 1 subnets
D 2.0.0.0 [90/307200] via 10.0.12.2, 00:00:32, Ethernet0/0
D 3.0.0.0/24 is subnetted, 1 subnets
D 3.0.0.0 [90/307200] via 10.0.13.2, 00:00:32, Ethernet0/1
C 10.0.0.0/8 is variably subnetted, 5 subnets, 2 masks
C 10.0.12.0/30 is directly connected, Ethernet0/0
L 10.0.12.1/32 is directly connected, Ethernet0/0
C 10.0.13.0/30 is directly connected, Ethernet0/1
L 10.0.13.1/32 is directly connected, Ethernet0/1
D 10.0.23.0/30 [90/307200] via 10.0.13.2, 00:00:32, Ethernet0/1
D 10.0.23.0/30 [90/307200] via 10.0.12.2, 00:00:32, Ethernet0/0

elements[8] (inet:ipv4Route *)
[0] C 10.0.12.0/30 gw:* metric:200 if:eth0
[1] C 10.0.13.0/30 gw:* metric:200 if:eth1
[2] D 10.0.23.0/30 gw:10.0.13.2 metric:307200 if:eth1
[3] D 10.0.23.0/30 gw:10.0.12.2 metric:307200 if:eth0
[4] C 1.0.0.0/24 gw:* metric:200 if:eth2
[5] D 2.0.0.0/24 gw:10.0.12.2 metric:307200 if:eth0
[6] D 3.0.0.0/24 gw:10.0.13.2 metric:307200 if:eth1
[7] C 127.0.0.0/8 gw:* metric:1 if:lo0

```

Figure 9: Scenario I - Comparison of router R1's routing table after the topology reached convergence.

## D Comparison: Scenario II - Topology Change Propagation

No.	Time	Source	Destination	Protocol	Length	Info
1	64.306108	10.0.13.1	224.0.0.10	EIGRP	143	Query
2	64.315117	10.0.13.2	10.0.13.1	EIGRP	60	Hello (Ack)
3	64.324000	10.0.13.1	224.0.0.10	EIGRP	99	Update
4	64.332947	10.0.13.2	10.0.13.1	EIGRP	143	Reply
5	64.342256	10.0.13.1	10.0.13.2	EIGRP	60	Hello (Ack)
6	64.350962	10.0.13.2	224.0.0.10	EIGRP	99	Update
7	64.351352	10.0.13.1	224.0.0.10	EIGRP	143	Update
8	64.359784	10.0.13.1	10.0.13.2	EIGRP	60	Hello (Ack)
9	64.360054	10.0.13.2	10.0.13.1	EIGRP	60	Hello (Ack)
10	64.580723	10.0.13.2	224.0.0.10	EIGRP	99	Query
11	64.589825	10.0.13.1	10.0.13.2	EIGRP	60	Hello (Ack)
12	64.614879	10.0.13.1	10.0.13.2	EIGRP	99	Reply
13	64.616164	10.0.13.2	10.0.13.1	EIGRP	60	Hello (Ack)

Figure 10: Scenario II - Captured EIGRP traffic between R1 and R3 displayed with Wireshark

#	Time	Relevant Hops	Name	ID / Source	Destination	Type	Length
1	50.000	R1 --> R3	EIGRP_QUERY_MSG	10.0.13.1	224.0.0.10	EIGRP	198 B
2	50.000 158 450	R3 --> R1	EIGRP_ACK_MSG	10.0.13.2	10.0.13.1	EIGRP	72 B
3	50.000 225 650	R3 --> R1	EIGRP_REPLY_MSG	10.0.13.2	10.0.13.1	EIGRP	198 B
4	50.000 384 100	R1 --> R3	EIGRP_ACK_MSG	10.0.13.1	10.0.13.2	EIGRP	72 B
5	50.000 441 750	R3 --> R1	EIGRP_UPDATE_MSG	10.0.13.2	224.0.0.10	EIGRP	110 B
6	50.000 451 300	R1 --> R3	EIGRP_UPDATE_MSG	10.0.13.1	224.0.0.10	EIGRP	154 B
7	50.000 574 550	R3 --> R1	EIGRP_ACK_MSG	10.0.13.2	10.0.13.1	EIGRP	72 B
8	50.000 584 100	R1 --> R3	EIGRP_ACK_MSG	10.0.13.1	10.0.13.2	EIGRP	72 B
9	50.000 641 750	R3 --> R1	EIGRP_QUERY_MSG	10.0.13.2	224.0.0.10	EIGRP	110 B
10	50.000 729 800	R1 --> R3	EIGRP_ACK_MSG	10.0.13.1	10.0.13.2	EIGRP	72 B
11	50.000 797	R1 --> R3	EIGRP_REPLY_MSG	10.0.13.1	10.0.13.2	EIGRP	110 B
12	50.000 885 050	R3 --> R1	EIGRP_ACK_MSG	10.0.13.2	10.0.13.1	EIGRP	72 B

Figure 11: Scenario II - Captured EIGRP traffic between R1 and R3 displayed in OMNeT++

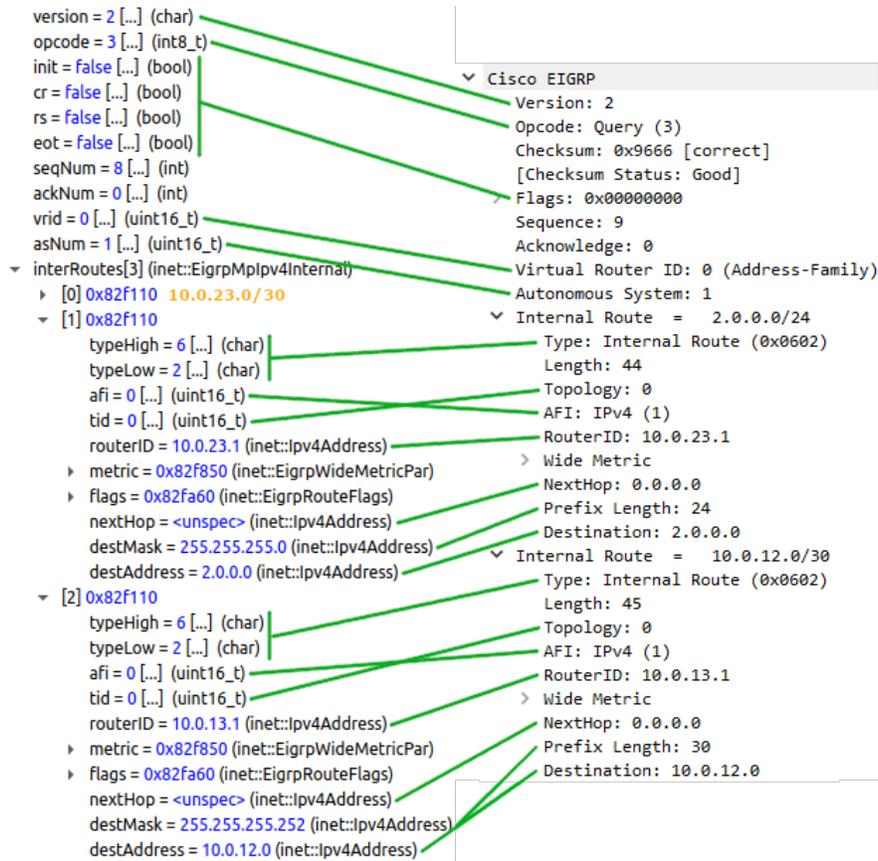


Figure 12: Scenario II - Comparison of Query message 1

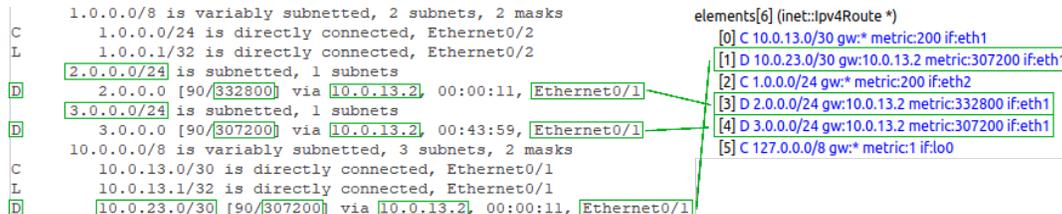


Figure 13: Scenario II - Comparison of router R1's routing table after the topology reached convergence. Content is identical to the initial state shown in Figure 8.

Cisco	OMNeT++	Description
1	1	A Query message originating on R1 advertising Active states for routes 10.0.12.0/30 and 2.0.0.0/24. Query in the simulation also includes route 10.0.23.0/30 which signifies an error in the DUAL operation. The content of these Queries is shown in Figure 12.
2	2	Acknowledgements for Query messages.
3	-	This Update message, originating on R1, advertises route 10.0.23.0/30 as unreachable. This is according to the <i>poison reverse</i> rule and it shows this route being correctly in the Passive state on the referential topology. Because this route is in the Active state in the simulation, router R1 has to wait for a Reply which delays this Update until message 6. Acknowledgment for this Update is piggybacked in the following Reply.
4	3	A Reply for the previous Query, containing R3's information about given routes. This message contains a metric for route 2.0.0.0/24 in both cases. Route 10.0.12.0/30 is also advertised with metric on the referential topology as router R3 did not yet receive any Queries from R2. This contrasts with the simulation where router R3 advertises 10.0.12.0/30 as unreachable because it has already received the Query from router R2. A metric for route 10.0.23.0/30 is also included in the simulation as it was present in the Query.
5	4	Acknowledgements for Reply messages.
6	5	Update message advertising route 10.0.12.0/30 with metric on the referential topology and as unreachable in the simulation.
7	6	Update message advertising unreachable routes due to the <i>poison reverse</i> rule. It contains route 2.0.0.0/24 in both cases, route 10.0.12.0/30 is present only on the referential topology and route 10.0.23.0/30, equivalent to message 3 on the referential topology, is present only in the simulation.
8, 9	7, 8	Acknowledgements for Update messages.
10	9	Query message advertising route 10.0.12.0/30 in the Active state for router R3. This message is caused by the arrival of a Query from router R2.
11	10	Acknowledgements for Query messages.
12	11	Reply advertising 10.0.12.0/30 as unreachable.
13	12	Acknowledgements for Reply messages..

Table 2: Scenario II - Analysis of the traffic between routers R1 and R3