Anonymity and Confidentiality in Secure Distributed Simulation

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Abstract

Research on data confidentiality, integrity and availability is gaining momentum in the ICT community, due to the intrinsically insecure nature of the Internet. While many distributed systems and services are now based on secure communication protocols to avoid eavesdropping and protect confidentiality, the techniques usually employed in distributed simulations do not consider these issues at all. This is probably due to the fact that many real-world simulators rely on monolithic, offline approaches and therefore the issues above do not apply. However, the complexity of the systems to be simulated, and the rise of distributed and cloud based simulation, now impose the adoption of secure simulation architectures. This paper presents a solution to ensure both anonymity and confidentiality in distributed simulations. A performance evaluation based on an anonymized distributed simulator is used for quantifying the performance penalty for being anonymous. The obtained results show that this is a viable solution.

Index Terms

Distributed Simulation; Secure Simulation; Anonymity; Confidentiality

I. INTRODUCTION

The complexity of many systems that are studied today requires scalable and efficient modeling and simulation tools. Whether we are dealing with the Internet of Things (IoT), military scenarios, or bio-medical systems, these models require huge computation times in order to obtain credible results [11]. Multilevel, hybrid and distributed simulation are all helpful techniques that can be employed to build scalable simulations by aggregating a pool of resources [12]. Of course, this flexibility has a price in terms of computation and communication overhead.

Traditionally, the research community working on distributed simulation focused on increasing the efficiency of Parallel And Distributed Simulation (PADS) engines to improve scalability. However, efficiency and scalability are not the only properties that matter in this context. In fact, confidentiality and anonymity can pay an even more important role in some contexts. For example, let us suppose that we are running a distributed simulation – say, a highly classified warfare simulation – over a pool of servers connected through the Internet. How can we make sure that the data exchanged among the hosts can not be intercepted or tampered with? Sniffing the interactions among the components of a distributed simulation can provide a lot of details on the structure of the simulated system. While this problem is obvious and can be solved using standard end-to-end encryption techniques (e.g., virtual private networks), there are particular situations where this is not enough. Indeed, encryption can hide the content of a message so that only the intended recipient is allowed to recover it; however, encryption alone may still leak the sender and receiver of a message in the form of their IP addressed and other sensitive information.

There are a number of scenarios where anonymity is important. For example, "what-if analysis" is an important support tool for military decision processes, and it requires both confidentiality and large-scale simulations to assess multiple war scenarios quickly; indeed, this kind of simulations must often be executed faster than real-time. Cyber-warfare is another prominent example that is getting a lot of attention. Cyber-warfare is about the actions by a nation-state (or another international organization) to attack and possibly damage the computing infrastructures or the communication network of an opponent. This is usually done by means of computer viruses/worms, distributed denial-of-service attacks or exploiting software vulnerabilities. In this scenario, the simulation assets that are used for managing critical infrastructures or planning the conventional military operations can be considered both sensitive and critical [20].

Of course, the trivial "solution" of centralizing all simulation components so that their interactions do not happen over the public Internet may not be acceptable. Not only centralized solutions are more difficult to scale, but in some cases large simulations are realized by federating components who are owned or controlled by different organizations that may not be willing to run their code out of their premises. Many modern simulation models are composed of components that are run on private or public computing infrastructures. As a matter of fact, many component-based simulations are distributed simulations. In general, anonymity can be a useful add-on in all those scenarios where the simulation working nodes are deployed on a network. The current trend is to exploit the computational capabilities offered by cloud computing. The possibility to take

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advantage of services which allow a dynamic and rapid re-configuration of the computation capacity, by adding and removing working nodes on demand, is fundamental for building simulation models with a certain degree of complexity. However, there is a number of threats concerned with the use of third party computation data-centers, whose interaction requires the use of Internet-based communication. Moreover, one of the top public cloud computing threats is concerned with malicious insiders. Even when a data center is trusted, we still might want to avoid tracking where the simulation components of a distributed simulation are executed.

Confidentiality and availability are other fundamental requirements for distributed simulation when dealing with sensitive data and applications. While simulation can be used to model and understand cyber-threats and cyber-warfare, strategies are needed to prevent that through these same threats unauthorized entities gain access to the simulated data or alter the simulation behavior. More specifically, availability is a main requirement in every distributed application and system. It is worth noting that availability and anonymity are, at least in part, correlated. In fact, being anonymous *can* prevent specific types of attacks by some malicious subjects (e.g. distributed denial of service attacks), since the attackers cannot know where simulation components are located and how to reach them.

In this work we discuss how to integrate the anonymity functionalities provided by a free software to enable anonymous communication (i.e., Tor) in the ARTÌS PADS middleware [3, 10]. This involves both modifying the design of the simulation middleware (in order to make it able communicating using Tor) but also preventing information leaks that could disclose sensible data of a simulation component to other parts of the distributed simulation. We evaluate the performance of the distributed anonymized simulation to quantify the overhead introduced by the Tor layer on the simulation execution time. Our results demonstrate that it is possible to build a distributed simulation that supports a high degree of anonymity of its components. It is worth noting that the studied approach does not solve all aspects related to the security of distributed simulation (or usage) of a software. It is also important to underline the price to pay in terms of performance for being anonymous. In this work, the cost of anonymity in distributed simulation is investigated and quantified.

The remainder of this paper is organized as follows. Section II describes the background and related works. In Section III we present the anonymous distributed simulator. Results from a performance evaluation are discussed in Section IV. Finally, Section V provides some concluding remarks.

II. BACKGROUND AND RELATED WORK

In this section we provide the background information that is required to understand the rest of the paper, including related works on simulation and security.

A. Background

1) Tor: is an open network protocol [4], for which free implementations are provided, that is designed and operated for improving privacy and security on the Internet. The aim of Tor is to make anonymous communications possible. This is achieved through an overlay network over the public Internet that is currently composed of about 6000 volunteer-operated servers. The basic component of Tor is the *onion routing algorithm* that allows end-to-end anonymity through multiple layers of encryption. In Tor, the user data (in our case, the simulation events) is encrypted multiple times and sent through a virtual circuit composed of a set of Tor relays (i.e., application-level routers, also called onion routers) that are randomly selected. A virtual circuit has a limited life span, meaning that after a certain amount of time a virtual circuit is no longer valid and must be rebuilt. It is worth noting that Tor encrypts both the user data and some metadata such as the IP address of the next destination of a packet. Each Tor relay can decrypt one layer of encryption only, so it can only know the next relay in the virtual circuit to forward the data to. In presence of correct operational security, and assuming that there are no vulnerabilities in all software components of the Tor network (including the communicating parties), this approach can hide the users' location from network surveillance and traffic analysis. Tor has been initially conceived for providing anonymity to users that access online services, but it can also be used to hide the true identity of servers. The servers that are reachable through the Tor network are called hidden services. The IP address of a service would obviously reveal its identity and location. For this reason, each hidden service is accessible only using its *onion address*, an identifier provided by the Tor network. An onion address allows clients to access a service without knowing its IP address. All client connections to hidden services are encrypted end-to-end, and therefore eavesdropping is not an effective attack method. A detailed description of Tor is outside the scope of this paper; a comprehensive introduction can be found in [6].

2) Parallel And Distributed Simulation: the traditional approach to the implementation of a simulation model is through a serial program. This means that a single execution unit is in charge of running the whole simulation model. In recent years, sequential simulations have shown many limitations [10] mainly in terms of lack of scalability when dealing with large and complex models. A Parallel and Distributed Simulation (PADS) takes advantage of multiple execution units to efficiently handle large simulations [16]. These execution units can be distributed across the Internet, or grouped as massively parallel computers or multicore processors. In the PADS approach, the simulation model is partitioned in submodels, called Logical Processes

(LPs) which can be evaluated concurrently by different execution units. More precisely, the simulation model is described in terms of multiple interacting entities that are assigned to different LPs. Each LP runs on a different execution unit, where an execution unit acts as a container of a set of entities. The simulation progress through the exchange of timestamped messages, representing events that must be exchanged among entities.

B. Related Work

Even if security is often listed among the requirements for creating reliable and scalable distributed simulations for real-time decision making [18], the research done on this topic is quite limited. In fact, more attention has been devoted to the usage of simulation for investigating systems security, that is clearly a totally different topic with respect to the problem addressed in this paper.

A large part of the research on the security of distributed simulations is strictly related to the High Level Architecture (HLA). The HLA is a general architecture that aims at improving the interoperability of distributed simulators [2] through the composition of software components called *federates*. In essence, a federate represents a portion of a (possibly large) simulation model. The main security issues of HLA are discussed in [15]. The authors investigate the usage of the IPsec protocol to provide confidentiality to the federates communicating through the HLA runtime infrastructure (RTI). Additionally, the authors envision the adoption of a public key infrastructure for access control on specific parts of the simulation model (e.g., the federation object model).

In [24] and [7], the authors discuss the security of distributed simulation and describe the trusted third party architecture that is implemented in the CERTI/ONERA RTI. The threat model considered by the authors assumes that each federate can trust some components of the RTI, but does not trust the other federate components. The proposed approach relies on secure domains and on the use of Generic Security Services Application Program Interface to secure communications between remote federates and the RTI.

More recently, in [26] the authors propose the usage of secure protocols (e.g., HTTPS) and an authentication framework based on a public key infrastructure to enable the execution of a specific HLA RTI on a cloud environment. In this case, the main goal is to provide data confidentiality and integrity of services.

Among the few research efforts that are not strictly related to HLA, in [21] the authors discuss the challenges in developing a security framework for the Agent-Based Environment for Linking Simulations (ABELS) framework. Many security aspects such as authentication, authorization and integrity of the distributed simulator are considered. Specifically, the proposed system is based on different security modes and a brokering security mechanism.

Finally, in [23] the same security aspects are discussed when applied to a distributed co-simulation in which different simulation models are interconnected together.

III. ANONSIM: AN ANONYMOUS SIMULATOR

This section presents AnonSim, a new distributed simulator that implements a method for anonymizing the communication streams among LPs. AnonSim is based on the GAIA/ARTÌS distributed simulation middleware [8] and relies on Tor for the exchange of information among LPs. We first provide some information on the GAIA/ARTÌS middleware, and then describe the modifications that have been applied to achieve anonymity.

In some systems it is possible to find that some LPs need to be anonymous while this might not be true for others. For the sake of simplicity, in this paper we assume that the anonymized version of the simulator is applied to all the LPs that are part of the distributed simulation (i.e., all LPs use Tor). Under the implementation viewpoint, this means that all the communications between the LPs must be done relying on the usage of the *onion address* of the LPs.

A. GAIA/ARTÌS logical architecture

ARTÌS [8] is a distributed middleware that allows seamless execution of sequential/parallel/distributed simulation models using different communication (e.g., shared memory, TCP/IP, MPI) and synchronization methods (e.g., time-stepped, conservative, optimistic). The GAIA framework [10] runs on top of ARTÌS and provides a high level application program interfaces that greatly simplifies the development of simulation models according to an agent-based approach. Furthermore, GAIA implements strategies for balancing the communication and computation load among the LPs based on adaptive partitioning, i.e., dynamic self-clustering of the simulation agents. This can reduce the communication overhead and achieve a more uniform usage of the computation resources, therefore speeding up the simulation.

B. AnonSim communication architecture

An important component of ARTIS is the SImulation MAnager (SIMA). The SIMA is used only for bootstrapping the simulation runs and, in this specific phase, it works as the central coordinator of the LPs. Specifically, it records information about all the LPs involved in the simulation, and at startup, the SIMA performs the role of simulation initiator. Thus, at the simulation bootstrap each LP must contacts the SIMA to receive information about the other participants in the simulation run, and the simulation starts only once the transmission channels between the LPs have been initialized.

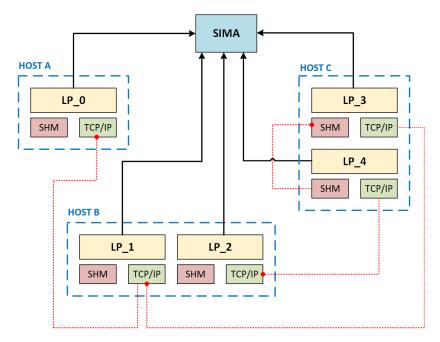


Figure 1. Communication architecture of ARTÌS.

Figure 1 depicts the communication architecture of ARTIS. Each LP contacts the SIMA to register itself (black lines in the figure). Since the SIMA knows in advance the number of LPs in each simulation run, it waits until every LP has registered. The simulation starts when each LP receives from the SIMA the information about all other LPs. After that, the nodes can start interacting by exchanging messages (red dotted lines). In the figure it is shown that LPs can communicate through two different mechanisms: shared memory (SHM in the figure), or (secured) TCP connections. Shared memory is used only among LPs that are executed on the same physical host.

In AnonSim, the SIMA receives only anonymized information about all the LPs, meaning that compromising the SIMA is not sufficient, e.g., for discovering the real location of the LPs. All TCP communications are tunneled through Tor by using the Socket Secure (SOCKS) protocol. Thus, each LP (and the SIMA) relies on SOCKS to interoperate with the simulation middleware and network communications, and this imposes that each host running a LP has a running local SOCKS server; in practice SOCKS provides encryption and anonymity for transmitted messages. All the simulation components are in fact Tor hidden services. As described above, the hidden service functionality is essential for providing anonymization of the simulation components. The interaction of SOCKS with the Tor protocol can be summarized as follows:

- Each LP connects to its local SOCKS server, instead of directly connecting to the destination hidden service (e.g., SIMA or other LPs);
- 2) The local SOCKS server sends a *connect request* to the receiver using onion address of the destination;
- 3) The hidden service (SIMA or LP) replies to the SOCKS server with an *answer code*: if the request is accepted by the destination then the SOCKS server tries to establish a connection to the destination hidden service.

Using this communication mechanism, each LP first registers to the SIMA in order to know how to contact other LPs. Due to the nature of the Tor network, LPs may have to retry several times the initial SOCKS connect request. Once the SOCKS response is received, an LP has its own connection to communicate with the SIMA. In its first message, the LP provides to the SIMA all the needed information for being contacted, such as its onion address and TCP port. Then the SIMA answers with a unique identifier that is specific for this LP. Once all information about each LPs have been collected, the SIMA broadcasts is formation of all LPs in the simulation run. Note that all the information above is completely anonymous. In fact, each LP is represented only by the identifier assigned by the SIMA (which acts as a pseudonym) and is reachable only using the onion address of its hidden service that is provided by Tor. Figure 2 summarizes the interactions during this initialization phase.

After the initialization, each LP establishes a connection to all other LPs, thus creating a complete anonymous undirected overlay graph. In particular, since each network connection is bidirectional, a LP instantiates a connection only with those LPs that have a lower identifier (the one assigned by the SIMA). This avoids the creation of redundant pairs of (bidirectional) network connections. After this step, the simulation can start. All the communications will pass through these SOCKS connections, which are kept anonymous by the Tor network.

AnonSim is available for peer review and it will be integrated in the next release of the GAIA/ARTIS simulation middle-

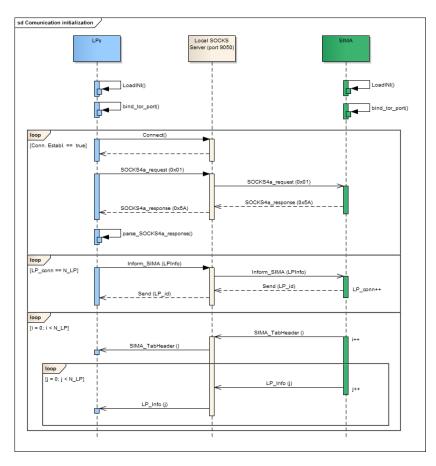


Figure 2. Sequence diagram of the communication initialization using ARTIS APIs. The interaction between the LP, the SIMA and the local SOCKS server are reported.

ware [3].

IV. PERFORMANCE EVALUATION

In this section we evaluate the performance of AnonSim to assess the impact of the network anonymization provided by Tor.

A. Simulation model

The model used in this performance evaluation is the "MIGRATION-WIRELESS" discrete event simulation model provided in the ARTIS package [3, 10]. The model is agent-based and consists of a set of Simulated Mobile Hosts (SMHs) wandering over a bi-dimensional toroidal space according to the Random Waypoint (RWP) mobility model [10, 22]. The SMHs interact by exchanging ping messages that are sent by each SMH to all SMHs that are within a fixed distance. From the simulator point of view, each SMH is implemented as a separate entity; the SMHs are initially randomly distributed across the LPs. The model uses the time-stepped synchronization scheme [10].

B. Simulation architecture

Given the expected use cases for AnonSim (i.e., running a distributed simulation over the Internet with confidentiality and anonymity requirements), the "MIGRATION-WIRELESS" model has been executed on three interacting hosts that are physically distributed through Europe. More specifically, each host will accommodate a single LP. The computational resources were supplied by two cloud providers. In particular, two instances were hosted by Amazon EC2 [5] and one by Okeanos [1]. The two EC2 machines were instances of the type *ec2.micro* located in Ireland (named *EC2.dublin*) and in Germany (named *EC2.frankfurt*). The remaining *Okeanos* host was physically placed in Greece. The detailed characteristics of the cloud instances used in this setup were:

- ec2-instaces: 1 vCPUs, 2.5 GHz, Intel Xeon Family, 1 GiB memory; network performances declared: low to moderate.
- okeanos: 4 vCPUs, 2.1 GHz, AMD-V Family, 4 GiB memory; network performances not specified.

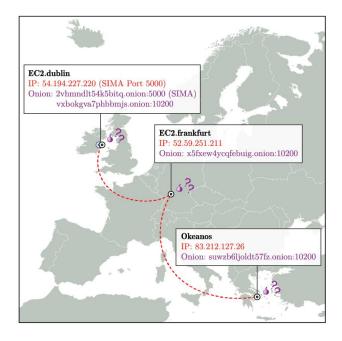


Figure 3. Simulation distribution of the hosts used in performance evaluation of AnonSim.

Figure 3 shows the geographical location of the hosts running the anonymized distributed simulation. For each host, the IP address (red) and the onion address (purple) are also shown. The SIMA was placed in the *EC2.dublin* instance. For this reason, this host has two different onion addresses: one for the SIMA and the other one for the LP.

It is worth noting that it is easy to record the path followed by the TCP segments used for delivering the simulation messages when the distributed simulation is run without using the anonymization provided by Tor, e.g., using applications like *traceroute*. On the other hand, in presence of the Tor network the path followed by the encapsulated TCP segments is harder to trace due to the use of virtual circuits and the characteristics of the Tor anonymization protocol.

C. Tor performances

The use of the Tor overlay network instead of the physical communication layer leads to a higher communication latency; therefore, an overall increase of the Round-Trip Time (*RTT*) is to be expected. We use the *tcpping* [25] software to get an estimate of the RTT. *tcpping* mimics the behavior of the classic *ping* application, but at the TCP layer. The use of *tcpping* is necessary since Tor does not support ICMP packets employed by the *ping* program.

Table I					
ROUND-TRIP TIMES OF STANDARD TCP/IP AND TOR COMMUNICATIONS: THE RESULTS ARE OBTAINED WITH 200 DIFFERENT ping, ONE EVERY 3 SEC.,					
BETWEEN OUR CLOUD INSTANCES.					
\overline{x} are the mean values: σ are the standard deviations					

	TCP/IP		Т	or
	\overline{x} (ms)	σ (ms)	\overline{x} (ms)	σ (ms)
EC2.dublin - Okeanos	92.91	0.75	326.42	278.52
Okeanos - EC2.frankfurt	67.14	0.16	282.74	104.83
EC2.frankfurt - EC2.dublin	20.84	0.20	540.74	54.5

Table I shows the RTTs between the hosts, using plain TCP (without Tor) and with Tor. As expected, Tor increases the network latency considerably, and also increases the variability of such latencies (i.e., introduces a wide standard deviation). Such high variability is due to the ephemeral nature of the virtual circuits provided by Tor. Such variability can be explained by considering several factors: the nature of the relays which compose the Tor network; the positions of the onion routers in a circuit; finally – and extremely relevant – the fact the circuits change over time. The latter implies a costly reconstruction of new circuits.

To illustrate the high RTT variability caused by Tor, we show in Figures 4, 5 and 6 the RTT distribution of 200 ping packets. We remark that the distribution has been obtained during a single execution of a simulation. Due to the nature of the Tor

network and the volatility of its virtual circuits, a considerably larger number of experiment would be needed to construct a reliable statistics. Despite this, we report our results to provide some quantitative evidence on the amount of delay that might be introduced by Tor, and that will affect the results provided in the remaining part of this section.

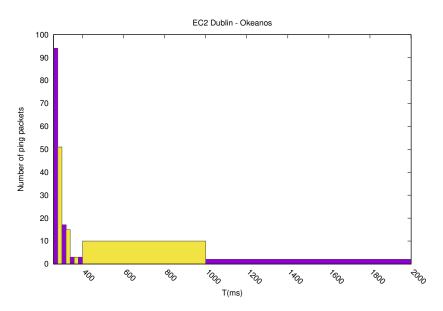


Figure 4. RTT frequency distribution of 200 ping packets (encapsulated by Tor) between the EC2.dublin instance and the Okeanos instance. The mean value (\bar{x}) is 326.42 ms and the standard deviation (σ) is 278.52 ms.

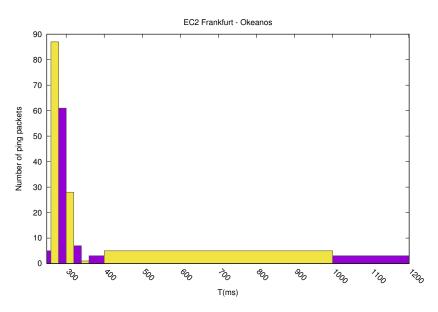


Figure 5. RTT frequency distribution of 200 ping packets (encapsulated by Tor) between the Okeanos instance and the EC2.frankfurt instance. The mean value \overline{x} is 282.75 ms and the standard deviation σ is 104.83 ms.

D. AnonSim execution results

The tests that have been performed to assess the performance of AnonSim are classified as follows:

- *TCP/IP* (or Tor) ALL_OFF: the load balancing mechanism provided by GAIA (i.e., the dynamic migration of SMHs based on self-clustering) is *disabled*. This means that every LP contains the same SMHs for the whole duration of the simulation runs.
- TCP/IP (or Tor) ALL_ON: the load balancing mechanism provided by GAIA is *enabled*. The standard self-clustering heuristic provided by GAIA is used; no tuning of the heuristic parameters has been performed.

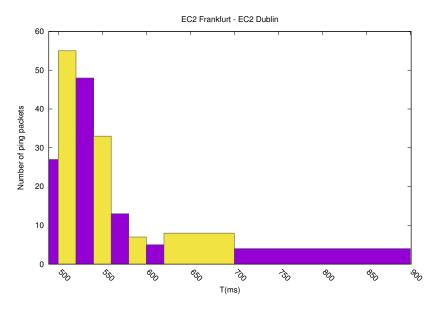


Figure 6. RTT frequency distribution of 200 ping packets (encapsulated by Tor) between the EC2.frankfurt instance and the EC2.dublin instance. The mean value \overline{x} is 540.74 ms and the standard deviation is 54.50 ms.

 Table II

 WALL-CLOCK-TIME (WCT) FOR THE EXECUTIONS OF THE SIMULATION MODEL WITH 3000 SMHs. ALL VALUES ARE IN SECONDS.

Configuration	Mean WCT	Std Dev	Min	Max	CI
TCP/IP ALL_OFF	130	1	128	132	1
TCP/IP ALL_ON	107	4	103	115	2
Tor ALL_OFF	924	414	508	1684	216
Tor ALL_ON	529	100	425	709	52

The results shown in the following of this section are obtained by averaging 10 simulation runs for each scenario.

In Table II we report the average WCT of the simulation model with 3000 SMHs, its standard deviation, the minimum and maximum WCT recorded over the 10 independent runs, and the half-width of the confidence interval (CI) for the mean WCT computed at 90% confidence level. We observe that, when run with load balancing turned off, AnonSim requires on average seven times the WCT required by the plain setup without Tor. As reported before, this is expected since the overhead added by the Tor virtual circuits is not negligible. The wide standard deviation of the WCT confirms that during the different sample runs, the Tor circuits changed, altering the overall performance of the simulator.

When adaptive load balancing is enabled, the speedup of the simulator using adaptive load balancing with respect to the base version not using it (computed as the ratio between {TCP/IP, Tor} ALL_OFF and {TCP/IP, Tor} ALL_ON) is approximately 1.75. Figure 7 shows the reduction of the wall-clock time and, more importantly that is obtained thanks to a significant reduction of the number of messages exchanged among the LPs, that is one of the beneficial effects of the dynamic self-clustering provided by GAIA. While the interaction between Tor and the self-clustering heuristics is quite difficult to analyze, and outside the scope of this paper, we can see that the total number of SMHs migrations (for self-clustering) requested by GAIA is on average 7,582.40 when Tor is enabled and 7,677.00 when it is not used. In other words, it seems that Tor does not affects significantly the ability of GAIA to provide communication and computational load-balancing.

Table III WALL-CLOCK-TIME (WCT) MEASURED FOR THE EXECUTIONS OF THE SIMULATION MODEL WITH 6000 SMHs. ALL VALUES ARE IN SECONDS.

Configuration	Mean WCT	Std Dev	Min	Max	CI
TCP/IP ALL_OFF	528	26	466	554	14
TCP/IP ALL_ON	167	13	157	198	7
Tor ALL_OFF	1586	826	939	3403	430
Tor ALL_ON	1022	203	736	1336	106

As shown in Table III, similar results are obtained when the number of SMHs is doubled. Figure 8 shows a WCT that is

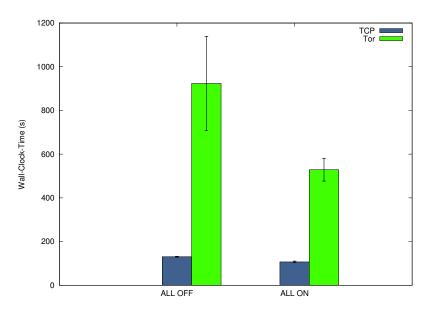


Figure 7. Average WCTs for the simulation model with 3000 SMHs.

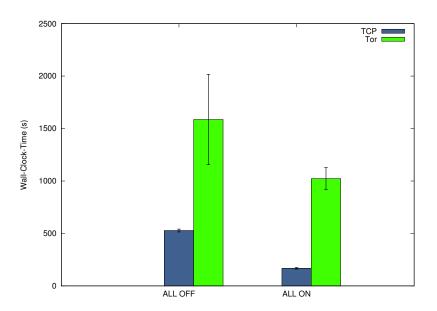


Figure 8. Average WCTs for the simulation model with 6000 SMHs and relative confidence intervals.

lower for the TCP/IP execution version with respect to the Tor one. In this case, the speedup obtained thanks to GAIA is 3.15 while in the anonymous version the speedup is 1.55. It is worth noticing that increasing the number of SMHs causes a higher workload on the LPs (whose number remained constant with respect to the case with 3000 SMHs) both in terms of communication and computation. This makes it more difficult for GAIA to improve the clustering of SMHs thus resulting in a higher amount of messages exchanged in the distributed simulator.

All the considerations reported above are confirmed when the amount of SMHs is set to 9000 (see Table IV and Figure 9). The speedup for the anonymous version is further reduced to 1.32 whilst for the TCP/IP version is 2.91.

E. Reliability

The main conservative synchronization mechanisms (e.g., the Chandy-Misra-Bryant NULL messages protocol) [9] and the time-stepped approach [14, 17] assume that the communication channel among the LPs is reliable, i.e., no message is lost or corrupted. This assumption is mostly true in conventional distributed simulations relying on the TCP protocol. However, the assumption is no longer true when we consider TCP connections that are encapsulated in Tor virtual circuits. Tor virtual circuits are ephemeral for security reasons; therefore, the periodic restructuring activity of the virtual circuits can result in

 Table IV

 WALL-CLOCK-TIME (WCT) MEASURED FOR THE EXECUTIONS OF THE SIMULATION MODEL WITH 9000 SMHs. ALL VALUES ARE IN SECONDS.

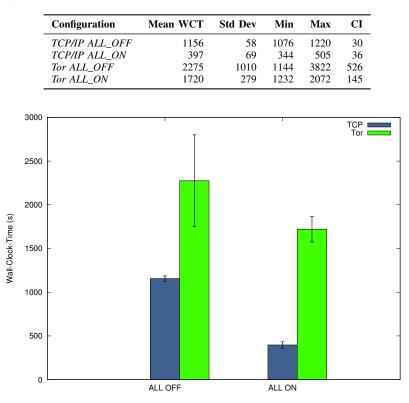


Figure 9. Average WCTs for the simulation model with 9000 SMHs and relative confidence intervals.

transient connection failures that are observed at the application level. Indeed, during our tests we discovered that the TCP connections encapsulated in the Tor virtual circuits are unable to deal with the underlying failure of virtual circuits. This affects the reliability of the simulator and the visible effect is that some simulation runs fail due to the unpredictable behavior of the communication infrastructure.

This issue can be addressed in may ways. Firstly, it is possible to implement solutions that address the more general problem of fault-tolerance in distributed simulation. For example, in [13] we have proposed an approach based on functional replication that is capable of tolerating crash-failures of computing nodes and offers some protection against Byzantine failures. Secondly, it would be possible to check the correct delivery of simulation events among the LPs by adding an additional reliability layer on top of the TCP-based communications. This mechanism should be implemented in each LP and it would be in charge of verifying that all the messages have been correctly received and, in case of failures, of triggering application layer retransmissions. Thirdly, it would be possible to port the whole simulator to a synchronization protocol such as Time Warp [19] that does not assume the reliability of communication channels. Of course, this would require a large scale refactoring of the GAIA/ARTÌS simulator; additionally, it has been shown that Time Warp may not be the most efficient protocol for all kinds of simulation models or execution architectures [14].

V. CONCLUSIONS AND FUTURE WORK

In this paper we described a mechanism that realizes confidentiality and anonymity in distributed simulation. The proposed solution has been implemented in a distributed simulator called AnonSim. AnonSim is based on the GAIA/ARTÌS simulation framework and the Tor network as the underlying system to anonymize and make untraceable all the communications. The proposed approach has been demonstrated as a viable solution, although at the cost of higher communication latencies, and a longer initialization phase. However, the benefits for anonymity and untraceability are evident in many distributed simulation scenarios.

As a future work, we plan to integrate in AnonSim the fault-tolerance mechanism based on functional replication described in [13]. This would make AnonSim more robust with respect to spurious failures introduced by the Tor network, while still supporting anonymity and confidentiality of communications.

REFERENCES

- [1] Okeanos: Grnet's cloud service. https://okeanos.grnet.gr.
- [2] IEEE Standard for Modeling and Simulation (M&S) High Level Architecture (HLA) Framework and Rules. IEEE Std. 1516-2000, pages i -22, 2000.
- [3] PADS: Parallel and Distributed Simulation Research Group. http://pads.cs.unibo.it/, 2018. University of Bologna.
- [4] Tor project: anonymity online. https://www.torproject.org/, 2018.
- [5] Amazon. Elastic cloud compute.
- [6] M. Backes, I. Goldberg, A. Kate, and E. Mohammadi. Provably secure and practical onion routing. In 2012 IEEE 25th Computer Security Foundations Symposium, pages 369–385, June 2012.
- [7] P. Bieber, J. Cazin, P. Siron, and G. Zanon. Security Extensions to ONERA HLA RTI Prototype. In In Proc. of the 1998 Fall Simulation Interoperability Workshop, pages 511–516, 1998.
- [8] L. Bononi, M. Bracuto, G. D'Angelo, and L. Donatiello. Scalable and efficient parallel and distributed simulation of complex, dynamic and mobile systems. In Proc. of the 2005 Workshop on Techniques, Methodologies and Tools for Performance Evaluation of Complex Systems, Washington, DC, USA, 2005. IEEE Computer Society.
- K. M. Chandy and J. Misra. Asynchronous distributed simulation via a sequence of parallel computations. *Commun. ACM*, 24(4):198–206, Apr. 1981.
- [10] G. D'Angelo. The simulation model partitioning problem: an adaptive solution based on self-clustering. Simulation Modelling Practice and Theory (SIMPAT), 70:1 – 20, 2017.
- [11] G. D'Angelo, S. Ferretti, and V. Ghini. Simulation of the Internet of Things. In 2016 International Conference on High Performance Computing Simulation (HPCS), pages 1–8, July 2016.
- [12] G. D'Angelo, S. Ferretti, and V. Ghini. Multi-level simulation of internet of things on smart territories. Simulation Modelling Practice and Theory (SIMPAT), 73:3 – 21, 2017.
- [13] G. D'Angelo, S. Ferretti, M. Marzolla, and L. Armaroli. Fault-tolerant adaptive parallel and distributed simulation. In Proc. of the 20th ACM/IEEE International Symposium on Distributed Simulation and Real Time Applications (DS-RT), pages 37–44, Washington, DC, USA, 2016. IEEE Computer Society.
- [14] G. D'Angelo and M. Marzolla. New trends in parallel and distributed simulation: From many-cores to cloud computing. *Simulation Modelling Practice and Theory*, 49:320–335, 2014.
- [15] A. Elkins, J. W. Wilson, and D. Gracanin. Security issues in high level architecture based distributed simulation. In Proc. of the 33Nd Conference on Winter Simulation, WSC '01, pages 818–826, Washington, DC, USA, 2001. IEEE Computer Society.
- [16] R. M. Fujimoto. Parallel discrete event simulation. Commun. ACM, 33(10):30–53, Oct. 1990.
- [17] R. M. Fujimoto. Parallel and distributed simulation systems, volume 300. Wiley New York, 2000.
- [18] R. M. Fujimoto. Research challenges in parallel and distributed simulation. ACM Trans. Model. Comput. Simul., 26(4):22:1–22:29, May 2016.
- [19] D. Jefferson. Virtual Time. ACM Transactions Program. Lang. Syst., 7(3):404-425, 1985.
- [20] D. McGrath, A. Hunt, and M. Bates. A simple distributed simulation architecture for emergency response exercises. In Ninth IEEE International Symposium on Distributed Simulation and Real-Time Applications, pages 221–226, Oct 2005.
- [21] G. A. Mills-Tettey and L. F. Wilson. Security issues in the abels system for linking distributed simulations. In Proceedings of the 36th Annual Symposium on Simulation, ANSS '03, pages 135–, Washington, DC, USA, 2003. IEEE Computer Society.
- [22] M. Musolesi and C. Mascolo. Mobility models for systems evaluation. In Middleware for Network Eccentric and Mobile Applications, pages 43–62. Springer Berlin Heidelberg, 2009.
- [23] K. Norling, D. Broman, P. Fritzson, A. Siemers, and D. Fritzson. Secure distributed co-simulation over wide area networks. In Proc. of the 48th Scandinavian Conference on Simulation and Modeling, 2007.
- [24] E. Noulard, J.-Y. Rousselot, and P. Siron. CERTI, an Open Source RTI, why and how. In Spring Simulation Interoperability Workshop, pages pp. 1–11, San Diego, US, 2009.
- [25] R. van den Berg. tcpping: test response times using TCP SYN packets. http://www.vdberg.org/ richard/tcpping.
- [26] Z. H. Zhang, X. D. Chai, and B. C. Hou. System security approach for web-enabled hla/rti in the cloud simulation environment. In 2011 6th IEEE Conference on Industrial Electronics and Applications, pages 245–248, June 2011.