Decentralized Detection of Violations of Service Level Agreements using Peer-to-Peer Technology

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***Abstract*—Critical networked services established between service providers and customers are expected to operate respecting Service Level Agreements (SLAs). An interesting possibility to monitor such SLAs is using active measurement mechanisms. However, these mechanisms are expensive in terms of network devices resource consumption and also increase the network load because of the injected traffic. In addition, if the number of SLA violations in a given time is higher than the number of available measurement sessions (common place in large and complex network infrastructures), certainly some violations will be missed. The current best practice, the observation of just a subset of network destinations driven by human administrators expertise, is error prone, does not scale well, and is ineffective on dynamic network conditions. This practice can lead to SLA violations being missed, which invariably affects the performance of several applications. In the present thesis, we advocate the use of Peer-to-Peer (P2P) technology to improve the detection of SLA violations. Such use is described using principles to control active measurement mechanisms. These principles are accomplished through strategies to activate measurement sessions. In this context, the thesis contains several contributions towards SLA monitoring, conceptually as well pragmatically. The findings show properties which improve the detection of SLA violations in terms of the number of detected violations and the adaptivity to network dynamics. We expect that such findings can lead to better SLA monitoring tools and methods.**

***Index Terms*—P2P-Based Network Management, SLA Monitoring, Active Measurement Mechanisms, Distributed Network Management**

I. Introduction

Computer network infrastructures have been improving dramatically in terms of capacity and accessibility. Likewise, the communication requirements of distributed services and applications running on top of these infrastructures have become increasingly accurate. Such requirements are usually described in Service Level Agreements (SLAs) established between service providers and customers. To ensure that SLAs are not violated, solutions that allow the service provider to monitor and troubleshoot the underlying communication infrastructure are crucial.

In SLA monitoring, accuracy and privacy are important aspects. In passive measurement, network conditions are said to be checked in a non intrusive way because no monitoring traffic is created by the measurement process itself. Passive measurement is realized, for example, inside network devices when they observe the passing traffic flows. Active measurement, on the other hand, is intrusive because it injects synthetic traffic into the network to measure the network performance. Measurement probes distributed along the network are the elements that, in active measurement solutions, inject such a synthetic traffic and compute the network performance. Active measurement mechanisms usually offer better accuracy and privacy than passive measurements. As a result, active is preferred over passive measurement in several scenarios. However, better accuracy and privacy come at a price: they turn active measurement solutions more expensive in terms of resource consumption (e.g., CPU cycle and memory footprint required by measurement sessions) inside network devices, in addition to increase the network load because of the injected traffic.

In practice, the common approach in feasible deployments of active measurement solutions consists of having the network operator activating only a subset of all available measurement sessions, thus enabling the observation of just a subset of all network flows, i.e., the set of all network flows is never covered entirely. This approach, however, does not scale well because it is still too difficult and labor intensive for the network operator to compute which measurement sessions should be activated given the set of critical flows that needs to be measured. Even worse, this practice completely fails in networks whose critical flows are too short in time and dynamic in terms of traversing network path, like in modern cloud environments. That is so because human operators are not just enough in computing and activating the new set of measurement sessions required every time the network traffic pattern changes. In this context, in addition to be labor intensive, the current active measurements practice usually covers only a fraction of the network flows that should be observed, which invariably leads to the damaging consequence of undetected SLA violations.

For example, the number of local available measurements results (and, consequently, detected violations) is still bounded by the number of activated measurement sessions. Thus, if the number of SLA violations is greater than the number of available sessions at a given time, only a fraction of the violations will be observed. Also, devices cannot share resources and knowledge about the networking infrastructure

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in order to take advantage of remote management information (*e.g.*, measurement results). In this context, this thesis aims at using P2P technology to provide the foundations to improve the detection of SLA violation through the distributed control of active measurement mechanisms. This thesis establishes a line of investigation based on hypothesis and the methodology described as follows.

II. Fundamental Research Question and Methodology

The goal of the present thesis is to investigate the decentralized detection of SLA violations using active measurement mechanisms in order to propose an approach to improve such detection. Different distribution approaches for network management have been studied for many years. Such approaches are usually grouped in three classes: centralized, hierarchical, and distributed ones. P2PBNM can be classified as a distributed approach since the management logic is performed across management nodes in a decentralized fashion. Thus, the alternatives to that would be either the centralization of such logic in a management station or the delegation of management tasks in a hierarchical approach. Centralized management is not considered in our study since it does not provide the necessary adaptivity to deal with large network infrastructures considering active measurement mechanisms. In this context, hierarchical control does not suit our purposes either since it also lacks such adaptivity. Besides that, the interfaces for the full control of active measurement mechanisms are usually provided only locally on the devices which also hampers the use of centralized and hierarchical approaches in the context of this thesis. To accomplish the proposed goal, we propose a fundamental research question and a research hypothesis:

- **Fundamental Research Question:** How to improve the network-wide detection of SLA violations in terms of the number of detected violations and the adaptivity to changes in network conditions?
- **Research Hypothesis:** The detection of SLA violations can be improved through the use of Peer-to-Peer (P2P) technology to steer autonomically the activation of active measurement mechanisms.

The general approach employed to carry out the investigation consists of to analyze how active measurement mechanisms are employed for SLA monitoring, considering the human administrators and the mechanisms *per se*, and to learn which are the shortcomings of the current best practice. The idea is to capture the common sense of human administrators in order to develop techniques that allow the network devices themselves better detect SLA violations. The method used on the investigation started with the execution of literature reviews on the network-wide control of measurement mechanisms and the employment of P2P technology on network management. After that, the proposed principles to control active measurement mechanisms and the strategies to activate measurement sessions were described. Finally, experiments were performed to evaluate the performance as well as to highlight properties of such principles and strategies.

The major contributions of this thesis are: i) An approach to improve the detection of SLA violations through the steering of the activation of active measurement sessions using local and remote past service level measurement results and resource utilization constraints; ii) The concept of destination rank as an approach to autonomically prioritize destinations for the activation of active measurement sessions using destination scores; iii) The concept of correlated peers to enable the autonomic provisioning of a P2P measurement overlay for the exchange of relevant active measurement results; iv) The concept of virtual measurement sessions to enable the sharing of measurement results among correlated peers in order to save network devices resources and to improve SLA monitoring coverage; v) The definition of decentralized strategies to steer the activation of active measurement sessions using P2P principles.

The rest of the paper contains a summary of the thesis work. The full text of the thesis can be found in [1]. Publications that contain results of this work were presented at CNSM 2012 [2], ICC 2013 [3], and AINA 2014 [4]. The literature reviews on the network-wide control of measurement mechanisms and the employment of P2P technology on network management are currently under review. Besides that, the paper presented at AINA was represented at the Internet Research Task Force (IRTF) & Internet Society (ISOC) Workshop on Research and Applications of Internet Measurements (RAIM). In addition, the work conducted in this thesis leaded to an Internet-Draft (I-D) [5], "Autonomic Networking Use Case for Distributed Detection of SLA Violations", proposed in the Network Management Research Group (NMRG) of the IRTF. Furthermore, 2 research projects funded by the Brazilian National Research Network (*Rede Nacional de Pesquisa* - RNP) were based in the investigation performed on the present thesis: one in 2014 edition of the RNP Monitoring Program (*Programa de Monitoramento*) and another one in the 2015 edition of the same program. Finally, also based in such investigation, the authors were granted by the Brazilian Internet Steering Committee (*Comitê Gestor da Internet Brasil* - CGI.br) to attend consecutively 9 IETF/IRTF meetings.

III. Principles of the Thesis

A pragmatical approach to deploy P2P technology in the control of the activation of active measurement sessions is to define principles to guide this deployment. In this thesis, we devise the utilization of 3 principles: i) local logic to prioritize destinations using past measurement results; ii) correlated peers to provision the measurement overlay; and iii) virtual measurements to optimize resource consumption. These principles lead to the introduction of key concepts to support a self-organizing, embedded P2P measurement overlay that uses the capabilities of the network devices to control session activation. In simple terms, our principles try to capture the common sense used by network administrators when using active measurement mechanisms to detect SLA violations. The

remaining of the section describes these principles and their implicit concepts.

Local Logic for The Destinations Prioritization Using Measurement Results. The utilization of past service level measurement results is our approach to establish if a destination is likely to disrespect SLOs (*i.e.*, violate the SLA). In order to establish that, we use descriptive statistics metrics to measure the closeness of past service level measurement results regarding the SLO for a given destination. For example, it is possible to use a composition of a measure of the central tendency (*e.g.*, mean) and a measure of spread (*e.g.*, standard deviation) as chosen metrics. If the past measurements results for a given destination are close to a SLO, then the probability of activating a measurement session in this destination should be increased. This is done by local logic, *i.e.*, an application that runs locally on the network devices. It is also important to assure that each destination is measured frequently, even if its measurement results are not close to the SLOs. In order to induce frequent probing on all destinations, we use the time elapsed from the last measurement for a given destination to increase the probability of this destination to be measured.

Correlated Peers for Measurement Overlay Provisioning. Service level measurement results are produced by active measurement mechanisms around the network infrastructure. In this context, human administrators usually can predict if SLA violations are likely to happen in a part of the network infrastructure using information from measurements of other parts of the network. This is possible because administrators can use their experience and knowledge to infer the relation among the links within the network infrastructure. In this context, service level measurements produced by active measurement mechanisms around the network infrastructure could be also shared by the devices to help the local measurement session control. However, it is necessary to assure that the remote results have local relevancy. In order to guarantee that, we use the concept of correlated peers. 2 nodes are considered as correlated peers (correlation is symmetrical) if the results of their measurements for a given destination are correlated. Hence, it is necessary to compare the local and remote results to verify whether they are in the same vicinity as the local measurements. This can be done using correlation functions, such as the Pearson product-moment correlation coefficient and the Spearman rank correlation coefficient.

Virtual Measurements for Resource Consumption Optimization. Our proposed solution to increase the number of SLA violation tries to capture one of the behaviors commonly employed by network administrators, the sharing of measurement results. Sometimes a single device cannot achieve the desired measurement coverage in isolation due to its own capabilities. Besides that, the administrator can choose not to achieve a defined coverage considering the device in isolation. This is usually done to save resources for main network functions, such as switching and routing. However, it is important to define which network devices are prone to share measurement results, considering their own capabilities, the quality constraints, and the available resources. In this context, sharing active measurement results among devices can improve SLA violation detection regarding the resource consumption and monitoring coverage. This sharing can be done by devices agreeing to exchange measurement results and contracting measurement session activations. We define a virtual measurement session as the use of results from remote measurement sessions by a peer as their own.

For more details, see Chapter 4 in [1]. The next section presents the details of the strategies to activate active measurement sessions using P2P technology.

IV. Strategies to Activate Measurement Sessions

The principles presented in Section III are defined to steer autonomically measurement session activation decisions. In order to accomplish these principles we define measurement session activation strategies, which are the expected behavior from the network devices concerning the control of active measurement mechanisms. We assume these mechanisms must be controlled without internal modification, *i.e.*, the strategies should be able to handle current versions of active measurement mechanisms. Thus, the strategies aim at increasing the efficiency of the detection of SLA violations solely through efficient measurement session activation decisions. This assumption increases the applicability of the present work.

We define 3 strategies to choose which destinations will be probed: measurement session activation based solely on local information, measurement session activation based on both local and remote information, and the use of virtual measurement sessions using the measurement overlay. Each strategy builds up on the previous one, increasing the used information. A priori, as more information from the network is used, the measurement session activation decisions capture better the service level violations. The remaining of the section presents the description of each one of the measurement session activation strategies.

Local Strategy. The local strategy is performed using only information locally available on a node. This information comes from past service level measurement results, which are used to compute scores for each destination. The local strategy is the simplest one, in which only 2 destination scores are used. The first score tries to capture that destinations which are closer to violate the SLA should have a higher probability of being probed in the following iterations. In more detail, the score uses the average of past measurement results (discounted over time) considering a sliding window. The second score aims at maintaining frequent measurements on destinations. Thus if a destination had not been measured recently, then it should be more likely to be selected in the next iterations. As the measurement results are updated dynamically, the strategy can adapt to changes in network conditions.

Local and Remote Strategy. The local and remote strategy is performed using information available from the local network device and received from other devices. Therefore, the main difference between this strategy and the local one is the source of measurement results. Now, in each iteration, there are 2 distinguished phases: peer topology phase and

measurement session activation. In the first phase, we use the concept of correlated peers (as described in Section III) to build a P2P measurement overlay. In this phase, there is a peer selection round, which determine the set of candidate peers to share measurement results. After determining actual correlated peers from candidate peers, the device starts to send its past measurement results for the correlated peers. In the second phase, the measurement session activation takes place using the locally collected information and also measurement results received from correlated peers.

Virtual Strategy. The virtual strategy enhances the concept of correlated peers in order to choose which peers are interesting to share measurement sessions with, *i.e.*, to have virtual measurement sessions with. The bulk of the computation, bandwidth, and storage needed to operate the virtual measurement session is contributed by the correlated peer. The virtual strategy builds up on the local and remote strategy, thus the peer topology and peer probing phases are also performed (as explained before). Peers partition the SLA monitoring tasks (*i.e.*, available destinations) for the set of destinations they are interested in and have no measurements. We consider a scenario of multiple devices which observe multiple events (active measurement sessions) and those devices need to perform measurement session decisions in a dynamic network. Hence, a contract protocol is employed to dynamically adapt the virtual measurement sessions to network conditions.

For more details, see [2–4] and Chapter 5 in [1]. The next section presents selected performance results.

V. Selected Performance Results

The focus of the experiments performed in the thesis is to evaluate the detection rate of SLA violations as well as the properties of the measurement session activation strategies. The use of P2P technology enable the use of local information, logic and data, to steer active measurement mechanisms. Such use is defined regarding the measurement session activation strategies, which vary in terms of the employed information and P2P features.

In the first selected experiment [2], we aim at determining the adaptation features of the control of the activation of local deployed sessions, thus the virtual strategy is excluded, *i.e.* there is only local activated measurement sessions. In order to accomplish that, we collected the number of SLA violations detected by nodes regarding a specific network environment scenario. In this scenario, initially there is not any SLA violation. Then, we increased the one-way delay on 4 access links for 40 cycles, which makes the end-to-end destinations that traverse these links to appear as SLA violators for the simulated active measurement mechanism. Then, we decreased the delay for these links and increased the delay for other 4 links for the same amount of cycles. This is done to simulate an almost instantly change in the placement of violations in the topologies, which is worst case situation for an adaptive approach. We chose the number of cycles in which the experimental scenario is changed in order to permit that the proposed strategies go through steady state.

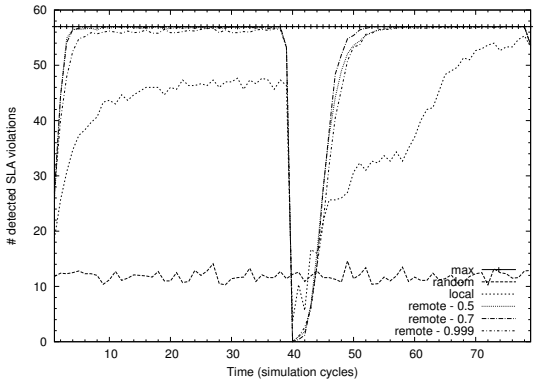

Fig. 1. Number of Detected SLA Violations. Adapted from [2].

The results for the first selected experiment are shown on Figure 1 considering a Hot-like topology (created using the Orbis topology generator [6]). In this figure, we present the mean raw number of detected SLA violations as a function of simulation cycles. The performance of measurement session activation strategies is depicted in the following curves: random strategy ("random"), local strategy ("local"), and local and remote strategy using as minimum correlation score: 0.5, 0.7, and 0.999 ("remote - 0.5", "remote - 0.7", and "remote - 0.999"). Besides the curves for the proposed strategies, we also present the maximum number of SLA violations that can be detected ("max"). The experiment shows that the proposed strategies behave as expected, without stability and convergence problems. As can be seen in Figure 1, the utilization of both local and remote information on measurement session activation decisions increases significantly the raw number of detected SLA violations in the experimental scenario. Clearly, even the unique utilization of local information (which can be view also as a baseline for the P2P strategies) has a better performance than the random placement. For more details, see [2] and Chapter 6 in [1].

In the second selected experiment [4], we aim at determining whether virtual measurements can increase the number of detected SLA violations over the maximum detections made by local measurements. In order to accomplish that, we collected the total number of SLA violations detected by nodes regarding a specific network environment scenario. In this scenario, we increased the one-way delay on 4 access links for 20 cycles, then we changed for other 4 links for the same amount of cycles. This increase makes the end-to-end destinations that traverse the changed links to appear as SLA violators for the simulated active measurement mechanism. We chose the number of cycles in which the experimental scenario is changed in order to permit that the proposed approaches go through their steady state.

The results for the second selected experiment are shown on Figure 2 considering a "4-post" Data Center topology (created

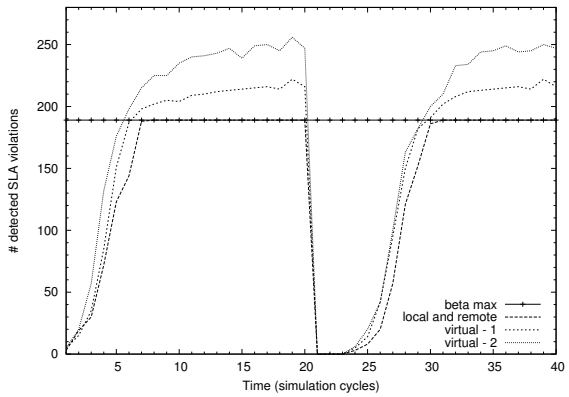

Fig. 2. Number of Detected SLA Violations Considering Virtual Measurement Sessions. Adapted from [4].

using the Facebook's data center network architecture [7]). The performance of virtual strategy is depicted in respect to the maximum number of virtual measurement sessions with the following values: 1 ("virtual - 1") and 2 ("virtual - 2"), as a function of simulation cycles. Results for the local and remote strategy ("local and remote") are depicted as baselines and the number of locally activated measurement sessions (β) is equal to 3. Besides that, we also present the maximum number of SLA violations that can be detected by local measurement sessions ("beta max"), *i.e.*, every activated session detects a SLA violation per cycle. The experiment shows that the virtual strategy behaves as expected, without stability and convergence problems. As can be seen in Figure 2, the utilization of virtual measurement sessions can increase significantly the number of detected SLA violations in the experimental scenario. Clearly, even the employment of just 1 virtual measurement is positive since it enables overcoming the constraint on the use of local resources (beta max). In this context, the adaptivity of the virtual strategy and the local and remote strategy are similar. For more details, see [4] and Chapter 6 in [1].

In the third selected experiment [3], we aim at determining the potential number of missed SLA violations as a function of the number of locally deployed probes (β) regarding a specific network environment setup. In this setup, we increased the one-way delay in access links using 3 different percentages on such links: 10%, 25%, and 50% (considering the local device view). This increase makes the end-to-end paths that traverse the changed links to appear as SLA violators for the simulated active measurement mechanism. Besides that, it is employed either only local performed measurements and local and virtual measurements. The maximum number of virtual measurements is set to 1 per node.

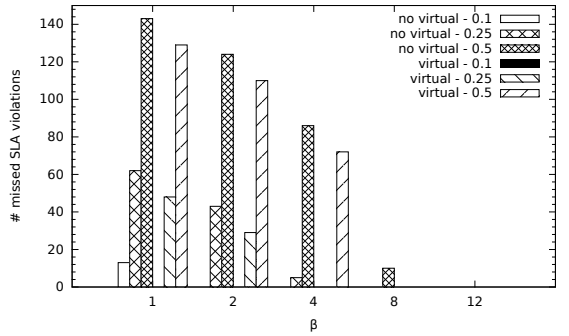

Fig. 3. Number of potentially missed SLA Violations. Adapted from [3].

The results for the third selected experiment are shown on Figure 3 considering an inferred Rocketfuel topology (created using using available data from the Rocketfuel project [8]). The curves depicted on Figure 3 represent the potentially missed SLA violations considering the changed access links and the utilization of coordination strategy: with the use of virtual strategy ("virtual - 0.1" for 10%, "virtual - 0.25" for 25%, "virtual - 0.5" for 50%) and without the use of virtual strategy ("no virtual - 0.1" for 10%, "no virtual - 0.25" for 25%, "no virtual - 0.5" for 50%). As can be seen in Figure 3, the utilization of the virtual strategy decreases the number of missed SLA violations in the experimental setup (less is better on Figure 3). Clearly, even the utilization of only 1 virtual measurement improves the SLA detection performance. For more details, see [3] and Chapter 6 in [1].

VI. Final Remarks and Future Directions

In the present thesis, we advocated the use of P2P technology to increase the potential number of detected SLA violations by active measurement mechanisms. In this context, we proposed 3 principles to steer management decisions regarding such mechanisms: the use of local logic to prioritize destinations using past measurement results, correlated peers to provision the measurement overlay, and virtual measurements to optimize resource consumption. These principles are accomplished through strategies to activate measurement sessions.

Our work is intended to be an initial step towards P2P-based control of active management mechanisms. We also intend to investigate how coordination features can enable composite measurement tasks. Besides that, refinements in the definition of correlated peers can be included to allow a more selective peering. For example, throttling of overlay traffic can be introduced for "popular" peers. Furthermore, there will likely be other interesting research opportunities in the context of this thesis. For example, information about correlated peers can have other uses, *e.g.*, allow inferences about the underlying (physical) topology.

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