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DOCTORAL DISSERTATION REVIEW

Title: Optimizing Critical Function Placement

to Ensure Resilient Network Services - Selected Problems

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1. Purpose and scope of the dissertation

This doctoral dissertation addresses a set of optimization challenges relevant in three different network contexts. The first context is the design of the control plane of SDNs (Software Defined Networks), which requires the optimal determination of the number of SDN controllers and the identification of their placement in the SDN data plane network. The second context is the design of a distributed probe system able to limit the impact of DDoS attacks to a given subset of network nodes, which requires the optimal determination of the number of probes and identification of their placement in a network. The third context is the setup of Service Function Chains (SFCs) on a given multi-domain network, which requires the optimal identification of the routing path of each SFC to minimize a given utility function.

All three contexts are timely and relevant to the information and communication technology (ICT) sector. The research is mainly theoretical, but it also includes a proof of concept in the context of the SFC provisioning. To solve the addressed optimization problems, the research presented in this dissertation uses graph theory, linear (and integer linear) programming, heuristics and game theory.

2. Structure and content of the dissertation

This dissertation is composed of 4 chapters where Chapter 1 is the introductory part while Chapters 2 to 4 describe the optimization methods developed for each of the addressed network contexts. In more detail:

- Chapter 1 presents the motivation of this dissertation research on each of the three network contexts providing already a state-of-art on each of them. Then, the chapter enumerates the original contributions of the dissertation. Then, the thesis of the dissertation is briefly presented. Finally, it presents the layout of the dissertation

Afousa

identifying the published research papers that have resulted from the work described on each of the next chapters.

- Chapter 2 describes the optimization methods developed in the context of the SDN control plane. The problem is studied as a SDN controller placement problem resilient to target node attacks. The problem is defined as a two-player game (between the SDN operator and the attacker) where the operator aims to choose the controller placement that minimizes the impact of the worst-case attack, while the attacker chooses the target nodes that maximize the impact of the best-defended controller placement. The novelty of this research is the consideration that both players, instead of choosing a single solution, aim to choose a probability distribution among different possible solutions. For that, two mathematical models for optimizing the probability distributions of the mixed strategy are proposed, together with a column generation procedure able to optimize the distributions for larger problem instances. The computational results are comprehensive and demonstrate that using the probability distribution approach provides gains to both players, but the resilience gains of the SDN operator are higher, on average, than the resilience impact losses obtained by the attacker.
- Chapter 3 describes the optimization methods developed in the context of probe systems for impact limitation of DDoS attacks. The optimization problem (named in the dissertation "Traffic Sentinel Placement") assumes the possibility of installing probes (they are named "sensors" in the dissertation, but I think the term is misleading) in nodes able to analyse and eliminate DDoS traffic in any of their links. Moreover, the addressed problem assumes that only a subset of nodes is to be protected (from DDoS attacks) and that it is too costly to place probes in all network nodes. Two variants of the probe placement problem are addressed: in the PQ problem, the aim is to identify a probe placement solution with a minimum number of probes to reach a worst-case attack impact value; in the PC problem, the aim is to identify a probe placement solution with a given number of probes that minimize the worst-case attack impact value of any DDoS attack. The chapter proves the NP-hardness of the probe placement problem. Then, two mixed integer models are proposed (one for each variant) together with two heuristics. The computation results effectively demonstrate the merits of each type of solution approach.
- Chapter 4 describes the optimization methods developed in the context of the SFC provision problem. The main novelty of the work is to study the problem in the context of a multiple domain network, where each SFC chain must be established on a simplified view of the resources that exist on each network domain, and the resources of each domain include the representation of network slices. In the addressed optimization problem, each SFC is defined with a set of required VNFs (Virtual Network Functions) defined in a sequence that must be fulfilled by the solution. The objective function is a linear combination of a traffic engineering objective (to minimize the maximum network link utilization) and a slice deployment objective (to minimize the number of required slices). An integer linear programming model is first proposed for the multicommodity optimization problem, together with a greedy heuristic. Then, different speed-up techniques are investigated to obtain more efficient heuristics. The computational results are enough to assess the trade-off analysis between the different solving techniques.

Afonso

3. Novelty and impact

All contributions of this dissertation in the three network domains add novelty to the previous state-of-art. In the context of the SDN control plane, the problem defined as a two-player game where both players aim to choose a probability distribution among different possible solutions (instead of choosing a single solution) is novel and required novel optimization methods. In the context of probe systems for impact limitation of DDoS attacks, the two problem variants are novel, they required novel optimization methods, and the conducted NP-hardness proof is also of value. In the context of the SFC provision problem, addressing it in the context of a multiple domain network is also novel and the proposed solution techniques are also novel.

The research included in this dissertation was published in 2 journal papers and 5 conference papers. The 2 journal papers were Journal of Communications Software and Systems (1 paper) and International Journal of Applied Mathematics and Computer Science (1 paper). This publication record demonstrates a reasonable impact of this research in the scientific community.

4. Critical remarks

My main remark to this research is that, although there are research contributions in each of the three addressed network contexts, there is no meaningful rationale justifying why these contexts were all addressed together. It is hard to identify communalities between the different contexts, both in the characteristics of the optimization problems addressed in the different network contexts, and in the solving techniques used to address them.

The lack of a final chapter with the overall conclusions of the whole set of research results is also an issue. Besides the overall conclusions, such chapter would be also the ideal place to summarize the topics for future research, which are in this dissertation identified in the last section of Chapters 2 and 4 (in fact, there is no topic for future research identified in Chapter 3). Moreover, such a chapter could help the reader to better understand my first remark (i.e., why the three network contexts were addressed).

Concerning the description of the state-of-art, this is split between Chapter 1 (as part of the motivation for each network context) and the first section of each of the other chapters, creating unnecessary repetition of some content.

In Chapter 3, the use of the term “sensors” for the elements of the “Traffic Sentinel System” is misleading. This is particularly important as part of the state-of-art in this chapter includes references in the context of Wireless Sensor Networks (WSNs).

My final critical remark is that the mathematical notation adopted on the different chapters is very different. Although I recognize that a perfect uniformization between the three chapter is impossible, an effort of better uniformization between chapters could have been conducted.

4. Summary assessment

The research described in this dissertation is of high scientific value in all the three addressed network contexts. The critical remarks presented above address issues on the way how the dissertation was written and organised, but do not put in question the merits of the described research. Mr. Dariusz Nogalski has proven his ability to model and solve optimization challenges that are timely and relevant in the ICT sector. Therefore, I consider that Mr. Dariusz Nogalski is fully qualified to be awarded the PhD degree.

Aveiro, 27 of May of 2025

Amaro Fernandes de Sousa

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