Universidade do Minho
Escola de Engenharia
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Development of a system compliant with the Application-layer Traffic Optimization protocol

January 2021

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Masters dissertation
Integrated Master's in Informatics Engineering

Dissertation supervised by
Pedro Nuno Miranda de Sousa

January 2021

ACKNOWLEDGEMENTS

I would like to firstly thank my advisor, professor Pedro Nuno Sousa, who was always present in any moment I struggled and required input to improve my work.

I would also like to thank my family for financially and emotionally supporting me through my academic journey, as well as the friends I've made along the way that made me see the best in people, and last but not least my dog Oscar who showed me unconditional love like only a dog could.

I finally also thank you, the reader. Since a work unused is no work at all, may you find some value in this one.

STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

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Paulo Edgar Mendes Caldas

ABSTRACT

With the ever-increasing Internet usage that is following the start of the new decade, the need to optimize this world-scale network of computers becomes a big priority in the technological sphere that has the number of users increasing, as are the *Quality of Service (QoS)* demands by applications in domains such as media streaming or virtual reality.

In the face of rising traffic and stricter application demands, a better understanding of how *Internet Service Providers (ISPs)* should manage their assets is needed. An important concern regards to how applications utilize the underlying network infrastructure over which they reside. Most of these applications act with little regard for ISP preferences, as exemplified by their lack of care in achieving traffic locality during their operation, which is a feature that would be preferable by network administrators and that could also improve application performance. However, even a best-effort attempt by applications to cooperate will hardly succeed if ISP policies aren't clearly communicated to them. A system to bridge layer interests therefore has much potential in helping achieve a mutually beneficial scenario.

The main focus of this thesis is the *Application-Layer Traffic Optimization (ALTO)* working group, which was formed by the *Internet Engineering Task Force (IETF)* to explore standardizations for network information retrieval. This group specified a request-response protocol where authoritative entities provide resources containing network status information and administrative preferences. Sharing of infrastructural insight is done with the intent of enabling a cooperative environment, between the network overlay and underlay, during application operations, to obtain better infrastructural resourcefulness and the consequential minimization of the associated operational costs.

This work aims to give an overview of the historical network tussle between applications and service providers, present the ALTO working group's project as a solution, as well as implement and extend upon their ideas, and finally verify the developed system's efficiency in a simulation when compared to classical alternatives.

Keywords: Application-Layer Traffic Optimization, Content Distribution Networks, Network Optimization, Peer-to-Peer, Traffic Engineering

RESUMO

Com o acrescido uso da Internet que acompanha o início da nova década, a necessidade de otimizar esta rede global de computadores passa a ser uma grande prioridade na esfera tecnológica que vê o seu número de utilizadores a aumentar, assim como a exigência, por parte das aplicações, de novos padrões de Qualidade de Serviço (QoS), como visto em domínios de transmissão de conteúdo multimédia em tempo real e em experiências de realidade virtual.

Face ao aumento de tráfego e aos padrões de exigência aplicacional mais restritos, é necessário melhor compreender como os fornecedores de serviços Internet (ISPs) devem gerir os seus recursos. Um ponto fulcral é como as aplicações utilizam os recursos da rede sobre a qual residem. Muitas destas aplicações não têm consideração por preferências dos ISPs, como exemplificado pela sua falta de esforço em localizar tráfego, e o contrário seria preferível por administradores de rede, bem como teria potencial para melhorar o desempenho aplicacional. Uma tentativa de melhor esforço, por parte das aplicações, não será bem-sucedida se as preferências administrativas não forem claramente comunicadas. Portanto, um sistema que sirva de ponte de comunicação entre camadas tem potencial para fornecer um cenário mutuamente benéfico.

O foco principal desta tese é o grupo de trabalho Application-Layer Traffic Optimization (ALTO), que foi formado pelo Internet Engineering Task Force (IETF) para explorar estandardizações de recolha de informação da rede. Este grupo especificou um protocolo de recolha onde entidades autoritárias disponibilizam recursos contendo informação de estado de rede, bem como preferências administrativas. A partilha de conhecimento infraestrutural é feita para possibilitar, durante operação aplicacional, um ambiente cooperativo entre redes overlay e underlay, para possibilitar uma mais eficiente utilização de recursos e a consequente minimização de custos operacionais.

Este trabalho pretende dar uma visão da histórica disputa entre aplicações e ISPs, assim como apresentar o projeto do grupo de trabalho ALTO como solução, implementar e melhorar sobre as suas ideias, e finalmente verificar a eficiência do sistema numa simulação, quando comparado com alternativas clássicas.

Palavras-Chave: Application-Layer Traffic Optimization, Content Distribution networks, Engenharia de Tráfego, Otimização de rede, Peer-to-peer

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ACRONYMS

ACL Access-Control List.
ADSL Asymmetric digital subscriber line.
ALTO Application-Layer Traffic Optimization.
ANE Abstract Network Element.
API Application Programming Interface.
AS Autonomous System.

BGP Border Gateway Protocol.

CAN Content Addressable Network.
CaTE Content-Aware Traffic Engineering.
CDN Content Distribution Network.
CDNI Content Distribution Network Interconnection.
CORE Common Open Research Emulator.
CPU Central Processing Unit.

DHT Distributed Hash Table.
DiffServ Differentiated services.
DNS Domain Name System.
DoH DNS over HTTPS.
DoS Denial of Service.
DPI Deep Packet Inspection.
DTO Data Transfer Object.

EGP Exterior Gateway Protocol.
EMEA Europe, the Middle East and Africa.

FCC Federal Communications Commission.
FTP File Transfer Protocol.

GNP Global Network Positioning.
GSLB Global Server Load Balancing.

HTTP Hypertext Transfer Protocol.

HTTPS Hypertext Transfer Protocol Secure.

ID Identifier.
IDMaps Internet Distance Map Service.
IETF Internet Engineering Task Force.
IGP Interior Gateway Protocol.
IP Internet Protocol.
ipv4 Internet Protocol version 4.
ipv6 Internet Protocol version 6.
IRD Information Resource Directory.
ISP Internet Service Provider.

JSON JavaScript Object Notation.

LSPD Label Switched Path Database.

MAC Media Access Control.
MPLS Multiprotocol Label Switching.
MTR Multi-Topology Routing.
MVC Model-View-Controller.

NETCONF Network Configuration Protocol.
NetPaaS Network Platform as a Service.

OSPF Open Shortest Path First.
OSPFv2 Open Shortest Path First Version 2.

P2P Peer-to-Peer.
PaDIS Provider-Aided Distance Information System.
PC Personal Computer.
PID Provider-Defined Identifier.
PoP Points of Presence.

QoE Quality of Experience.
QoS Quality of Service.

RAM Random-Access Memory.
RBAC Role-Based Access Control.
REST Representational state transfer.
RFC Request for Comments.

RTT Round-Trip Time.

SDN Software Defined Networking.
SNMP Simple Network Management Protocol.
SQL Structured Query Language.

TCP Transmission Control Protocol.
TED Traffic Engineering Database.
TLS Transport Layer Security.

URL Uniform Resource Locator.

XMPP Extensible Messaging and Presence Protocol.

1 INTRODUCTION

1.1 CONTEXT AND MOTIVATION

As society as a whole advances, so does seem to increase the individual's quality of life, which in turn increases the standard to be expected from the society he lives in. As such, technology itself must quickly adapt to the needs of the people it serves, whichever they may be - educational, medical, logistical, just to name a few - and consistently create or improve upon solutions that inevitably change the day-to-day living of the many that use or indirectly reap the benefits of such solutions. A particular example that is still fresh in this generation is in the relationship between people and computers - where they may have been nonexistent a century ago, reserved for industries fifty years ago and valuable household commodity a few decades ago, it is now common to see a family home with more than a dozen computers, with a variety fitting for the many kinds of problems they can solve. The increased number of computers and their expected functionalities has made it so computer networking as a whole has to be improved upon.

The internet allows computers to connect to one another in a worldwide network that applications can use to further increase their possibilities. However, when certain applications go unchecked it becomes very difficult for *Internet Service Providers (ISPs)* because such applications can create traffic which is either impossible, infeasible, or too costly to manage. This issue is further exacerbated when considering the scale of the next decade, where Cisco predicts that by 2022 global internet users will make up 60 percent of the world's population, and global IP traffic will reach 396 exabytes per month [1]. The problem of network management will thus increase in difficulty due to the sheer scale of Internet usage, and traffic engineering solutions are then required to provide certain service standards to applications, e.g., the *Differentiated services (DiffServ)* architecture, and more recently [2] and [3].

Considering a network of computers which are running applications to fit a given use case for the user, such as transferring a file, watching a real-time video, or consuming the content of a given social network, these applications are responsible for creating traffic that must be supported by the underlying network infrastructure, meaning all the hardware and software that is utilized by given companies to provide to end users the ability to communicate with each other. These applications can be thought of as citizens of a communications facility that provides the service of accessibility to other citizens, and there is a common incentive in maintaining this facility in such a way that keeps the service up to its standards. As such, and like any other community-shared facility, it must be maintained by the owners, and part of it includes creating and enforcing policies that uphold the facility's quality. During the runtime of an application, the way it is programmed to operate has impact on the traffic it generates on the network, and thus how resourceful it is with the shared domain it uses. The logic of the program dictates how the shared network is used to achieve a given goal, and how it accomplishes it can be more or less preferable by the service providers - for example, application decisions such as which hosts to consume a service from, at what time of the day some traffic is generated, or how much traffic is needed to achieve a use case, have a concrete impact on the shared network structure. *Peer-to-Peer (P2P)* applications are an infamous example of a kind of application that often makes decisions that are not preferable by ISPs. These applications create overlay networks, which are abstract networks constructed on top of the underlying network that supports it, and on which the application's logic runs on, essentially making it infrastructure-agnostic. Historically, P2P traffic has not been preferable by ISPs due to its unpredictable and hard to manage nature. Indeed, if P2P applications simply keep an overlay connection between peers that does not span more than a few hops, whilst ignorant to them being, for example, either direct network links or spanning multiple Autonomous Systems (ASs) in the underlay, the generated traffic is always at risk of being inefficient and too taxing on the supporting infrastructure - for example, by neighboring other peers which reside outside network borders, which are more infrastructurally expensive to reach. As global file-sharing traffic currently uses around 7 exabytes per month (including P2P-based file-sharing) [1], and BitTorrent alone makes up 27% percent of total upstream volume of traffic [4] it's in the best interest of both ISPs and P2P applications a way for the overlay and underlay levels to operate in synergy, i.e., how should the layers combine efforts to guarantee that their needs are met in a sustainable manner.

Current consumer trends suggest that media consumption will make up a considerable part of global Internet traffic. In fact, Cisco predicts that, by 2022, more than 82 percent of all consumer Internet traffic will be dedicated to Internet video streaming and downloads, and *Content Distribution Networks (CDNs)* will carry 72 percent of all Internet traffic [1]. CDNs act by injecting content geographically nearby end users to increase availability and reduce total traffic usage, and are an example of how applications can better leverage the shared domain's resources to achieve their goal. The CDN's management layer can optimize its application behaviour in ways that are advantageous to both applications using the CDN and the shared network structure, and such ways include what edge server to cache data to, how to efficiently match end users to appropriate edge servers, or how to increase service reachability among other CDNs. Thus, much like P2P networks, content distribution networks could also greatly benefit from cooperative interactions with network providers. These optimizations should be made by the parties which have economical interest in guaranteeing good performance of the overall ecosystem, i.e., those acting on the over and underlay, and should seek to, resorting to application and network administration input, understand how to utilize the given network resources to achieve functional requirements in a way that is cheap, effective and sustainable.

More broadly, most kinds of applications that generate traffic on a network could benefit from input by entities which know how such network is structured and what political and administrative biases exist. Of course, a one-sided approach could also exist to optimize resourcefulness of the network structure - applications could use an independent internal logic that utilizes measurements and its, albeit limited, knowledge of network details to better aid their decisions, and likewise ISPs can attempt to throttle, block, or generally apply traffic engineering. In fact, these one-sided approaches are precisely what happens currently, but this work aims to argue for a two-sided cooperative approach.

In short, the issue that motivates this thesis is the lack of proper cooperation between the overlay and underlay levels in the task of optimizing traffic that originates from decisions that occur at the application level, e.g., peer selection for file retrieval in file-sharing P2P applications, software distribution mirror selection, CDN provider server or cache redirections, high traffic load scheduling, etc. This problem is not new to the *Internet Engineering Task Force (IETF)*, who devised a working group to explore possible IETF standardization on traffic localization after test results concluded that P2P applications that select peers based on exclusive network information provided by ISPs could reduce network infrastructural and administrative costs as well as increase application download rates [5]. Such working group devised a request-response protocol by the same name, *Application-Layer Traffic Optimization (ALTO)*, where clients could query authoritative and trustworthy servers on information that regards to the underlay structure where the client operates. While the tussle between P2P applications and ISPs were the motivation for the ALTO working group to be created, the benefits of a standardized, maintained, and well provided system for network information querying and guidance on traffic-related decisions could help create the vision of ISPs and applications cooperating for mutual benefit, being thus advantageous for more than P2P applications - in essence, it would be a helpful system for any situation where a decision could be optimized with the addition of proper insight on network infrastructure. This work then focuses on tackling the theme of application-infrastructure cooperation on the Internet, with particular focus on presenting, implementing and improving the ALTO protocol as a cooperation enabler.

1.2 OBJECTIVES

The main objective of this thesis is to develop a working system that adheres to and expands upon the ALTO working group's devised protocol and architecture. The starting point will be a preexisting software project that served as a proof of concept to the strategy of traffic optimization at the application layer, which will now be extended in three ways: firstly, by restructuring and documenting the existing code in order to, through the compliance with the standards of object oriented programming and software development guidelines, present a solution that could be continuously maintained and modified; secondly, by further expanding on the software's functionality, e.g., adding more types of cost metrics, specifying meta-data which give the resources a time-specific applicability, specifying means of synchronizing data among servers, restricting user interaction via access control methods, etc); thirdly, by specifying and implementing a network data supply component to the architecture, as one has not been formally defined by the ALTO working group. Whilst expanding upon the working group's devised solution is indeed a goal, it is also important that the developed work complies with the specifications it is based on, so the work done by the IETF in regards to documentation and general reasoning of the protocol remains consistent with this implementation, with further additions being reasoned in this work.

With the intent of completing its main goal, this work's partial objectives were devised as follows:

- Literature review in regards to application-level traffic optimization and the co-operation - or lack thereof - between overlay networks and the underlay they operate on. More specifically, an understanding of what the problem entails, the consensus on the existing issues, and an overview of currently proposed solutions.

- Complete overview of the ALTO working group's current work. More specifically, an overview of both their existing RFC documents and currently active internet drafts (at the time of writing).
- Familiarization with the existing system to be worked on and definition of both a new system architecture which complies with and extends upon the ALTO solution, as well as the new function modules to be added and how they should operate.
- Implementation of the devised solution.
- Construction of a realistic network simulation scenario and prototype applications to base the experiments in - this includes a P2P and server-client file sharing applications.
- Testing of the implemented solution within a simulation scenario, and how it compares with other traditional methods in regards to achieved network infrastructural resourcefulness and client application performance.

1.3 CONTRIBUTIONS

This thesis's contributions include a working implementation of the ALTO protocol as specified by the working group of the same name, which includes functionally extensions, as well as the implementation of a devised architecture to fulfill the ALTO working group's proposed idea of layer cooperation, that includes a network status supply, resource access control, and domain synchronization layers. Additionally, the accomplished experiments in a simulated environment served as empirical proof of the usefulness of an ALTO system for layer cooperation, as it was able to display what is to be gained by using the proposed approach over traditional ones in regards to application performance and optimal network resourcefulness.

1.4 THESIS ORGANIZATION

This dissertation will be organized in six chapters, as follows:

- **Introduction**: Provides context to the tussle between applications and Internet providers, as well as an argument for the necessity to fix this issue to reach a sustainable environment for both parties. Coupled to this, the dissertation's main goal is presented.

- **State of the Art**: Displays the existing theory related to popular technologies or overall concepts that could leverage the ALTO protocol for improved functionality and/or performance; secondly, displays existing proposed solutions to traffic optimization at the application level that do so using network information with and without close underlay cooperation; thirdly, overviews the ALTO working group's proposed protocol and architecture.

- **System architecture and developed mechanisms**: Presents the devised system's functional and non-functional requirements, as well as an overview of the planned architecture.

- **Implementation**: Provides reasoning to the decisions that were made in the task of implementing the specified project.

- **Experiments**: Overviews the planned simulation scenarios, how they were materialized, how the related tests were performed, and their results.

- **Conclusion**: Presents a critical analysis of the simulation test results, and how they change the previously proposed hypothesis. Finally, it presents the results of this thesis in regards to what objectives were completed, the general conclusions that were retrieved, and future work.

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