論文の内容の要旨

論文題目

Analysis and Management of the Internet based on Data Flow Profiling

（データフロープロファイリングに基づいたインターネットの解析と制御）

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（本文）

Many applications and services have been developed over the Internet, and it becomes increasingly important to provide highly stable, available, and scalable service as the Internet has become a fundamental infrastructure for modern society and industry in this couple of decades, Therefore, Internet-wide distributed systems such as overlay networks and peer-to-peer (P2P) systems have been proposed to achieve higher stability, availability, and scalability. However, there exists a gap between the application layer and the network layer (a.k.a. layer 3) in network operations and management such as traffic engineering because these Internet-wide distributed systems construct their own structures at the application layer over the network layer. Unlike the traditional client-server model with the end-to-end architecture, these distributed systems override the routing policies at the layer 3 network by relaying and routing traffic at the application layer. This makes them difficult to detect, monitor, and control the traffic of distributed systems by layer 3 operators. The underlying cause of the problem with this gap is that the routing functionality is provided at both the application layer and the network layer in distributed systems, while each layer is independent of each other according to the layer separation architecture of the OSI reference model unless two different layers provide an identical functionality. Thus, it is a crucial challenge to bridge the gap between the application layer and the network layer to achieve network operator-friendly Internet-wide distributed systems. In this thesis, we highlight two types of gap between the application layer and the network layer in network operations and management; lack of underlay network information such as topology, link capacity, and cost information for the optimization of the overlay structures at the application layer, and insufficient and immature technologies in operations and management at the network layer for Internet-wide distributed systems such as traffic engineering and anomaly detection at the network layer.

Regarding the former type of gap, distributed systems such as P2P applications frequently utilize a large amount of network resources and cost more from the layer 3 core network operators' viewpoint because they do not take into account the routing policies and economics at the network layer. Moreover, they may utilize a detoured path that is disallowed or unexpected by layer 3 network providers. The Application-Layer Traffic Optimization working group in the Internet Engineering Task Force has worked on the standardization of an application-layer traffic optimization service that provides applications with information to perform better-than-random initial peer selection of P2P systems and node selection of other applications such as content delivery networks. However, the working group does not focus on the cost configuration between different administrative domains, i.e., autonomous systems (ASes), responding to the complex inter-AS policies. Therefore, we propose an AS relationships estimation method to provide applications with the inter-AS cost information Most network providers cannot disclose their relationships because the interconnections are established by their commercial contracts. The proposed method estimates AS relationships from publicly available AS-level topology datasets according to a simple traffic exchange model. Unlike the approach of the existing methods to infer AS relationships using AS paths, we adopt the simple traffic exchange model because the exchanged traffic volume is the fundamental basis of the AS relationships that the relationships between interconnections ASes are determined by the (a)symmetricity of the exchanged traffic volume. In this thesis, we demonstrate the proposed method outperforms the existing AS relationships inference methods, especially in peering links. We also discuss the advantages of the proposed method over the existing methods in the application-layer traffic optimization that the proposed method enables to estimate the relationships of invisible links not contained in the set of AS paths in publicly available datasets.

Network operators have employed traffic classifiers and anomaly detectors in their networks to bridge the latter type of gap and to improve operations and management at the network layer for Internet-wide distributed systems. However, many traffic classifiers and anomaly detectors rely on deep packet inspection, and consequently, they are not tolerant to the encryption of application data and they have some privacy issues raised by packet inspection. Moreover, maintaining the up-to-date signatures for each application takes a huge effort though various network applications including distributed systems run on the Internet. Thus, these existing tools do not capture the characteristics of Internet-wide distributed systems and they are not sufficient and mature for these systems. In this thesis, we develop an application traffic profiling method with traffic causality graphs (TCGs) that focuses on the temporal and spatial causality of flows of network applications to capture the characteristics of the distributed systems without inspecting packet payload. A key idea of TCGs is to focus on the causality of individual flows composed of different application protocols rather than a set of host flows. This idea enables us to analyze temporal interactions between flows, such as the temporal manner of flow generation by identical application programs and interactions between incoming and outgoing flows. In order to achieve automated profiling with TCGs, we adopt a graph mining approach to extract discriminative patterns in TCGs, and a similarity measure to identify the application of a TCG. We demonstrate the effectiveness of TCGs for profiling network applications in case studies and the automated profiling results with ground truth datasets.

Thus, we have worked to bridge the gap between the application layer and the network layer in network operations and management in the existing dirty slate architecture. There is another conceivable approach to solve the cross-layer problem by redesigning a clean slate networking architecture as several architectures such as content-centric network and named data networking have been proposed. However, it takes a lot of time and effort to replace the existing architecture with them. Therefore, we focus on solutions in the existing dirty slate architecture. In addition to the focus on the existing dirty slate architecture, we do not adopt a cross-layer dependent approach but a rough approach based on better-than-nothing principles to bridge the gap. This is because the cross-layer dependent approach has a difficulty in deployment and it requires an operation-related informational standard as well as a protocol specification standard. We illustrate the problem with the cross-layer dependent approach by domain name system (DNS) delegation relationships analysis in the IPv4 and IPv6 coexisting Internet. The domain name resolution procedure following the DNS delegation structure depends on the underlay protocol (i.e., IP), and consequently, an operation-related informational standard is required to support the coexistence of multiple underlay protocols. Since the DNS is a key infrastructure on the Internet, which is a tree-structured directory service to look up resources, such as corresponding IP addresses, from domain names and many services and systems, such as Web services and E-mail systems, deeply rely on DNS, there is an operation-related informational standard to guarantee the domain name resolution in in the IPv4 and IPv6 coexisting Internet; RFC4472 defines that every zone should provide at least one IPv4-enabled authoritative servers, domain name resolution with IPv4 is guaranteed as long as authoritative servers are operated according to RFC4472. Note that RFC4472 does not define IPv6-related configurations in terms of the connectivity of authoritative servers. Therefore, domain name resolution with IPv6 is not guaranteed, and it depends on the operating policy and configurations of each zone. In this thesis, we employ the DNS lookup graph that represents the domain name lookup procedure as a labeled directed graph to illustrate the difficulty in the deployment of a new underlay protocol in the cross-layer dependent approach by showing trends of the DNS lookup path in resolving A and AAAA records with IPv4 and IPv6 transport protocols using the datasets measured before, during, and after World IPv6 Day, and after World IPv6 Launch. Note that World IPv6 Day and World IPv6 Launch are worldwide IPv6 events to test and deploy IPv6 on the real Internet environment in 2011 and 2012.

In summary, this thesis consists of three parts: 1) inter-AS economics (i.e., AS relationships) estimation on the AS-level Internet topology to provide applications with the underlay cross-domain cost, 2) Internet application traffic profiling with a graph mining approach from the causality of flows to improve the operations and management at the network layer, and 3) DNS delegation relationships analysis to shed light on the problem with the cross-layer dependent approach and to support the approach based on better-than-nothing principles.