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（様式３）

博士論文の要旨

氏　　名　谷口　篤

論文題目　Dynamic network service control and management techniques across multi-provider networks

Communication networks are now an essential infrastructure of society. Communication networks consist of various kinds of networks operated by telecommunications operators, content providers, and cloud operators, and various network services (e.g., hybrid cloud or software-defined wide area network (SDWAN)) are constructed across multi-provider networks. Such multi-provider networks are usually configured and operated statically.
Dynamic Network Service (NS) control and management across multi-provider networks allow resource utilization and operability to be provided more efficiently. Service requests from users are sent to the network service management, which then selects the network that meets the requirements and notifies the network controller of each provider. The suitable route within the provider networks is selected as a result. This dynamic network service control and management mechanism reduces human work load and significantly improves overall work efficiency. Networks constructed across multi-provider networks are expected to be used for in various services (e.g., automated driving of vehicles, remote drone control, and remote surgery). For such applications, reliability is crucial in order to eliminate emergency accidents.
However, there is currently no established method for providing NS across multi-provider networks dynamically and for assessing their reliability although NS deployment across multi-provider networks has been extensively studied in academia. To manage services with appropriate network reliability across multi-provider networks, each provider needs to identify the services across the providers, and knows which route the services take among networks. NS deployment across multi-provider networks also should be defined in the global standardization. However, the current documents, especially those in the Network Functions Virtualisation (NFV) field, focus on a single operator case, and no work addresses practical aspects.
This dissertation describes four use cases featuring multi-site NFV provided by multiple providers in order to clarify what kinds of services should be considered namely, (a) a basic use case, (b) modification to the Wide Area Network (WAN) connectivity resource, (c) NS for end-to-end (E2E) service across two WANs, and (d) NS expansion to other NFV Infrastructure (NFVI)-Point of Presences (PoPs).(a) The basic use case is a use case to deploy NS at each site and connect the network connectivity between the two sites. (b) The modification to the WAN connectivity resource is a use

case to increase the capacity of an existing NS as the workload on the current NS has become high. (c) The NS for E2E service across two WANs is a use case to select an appropriate Virtual Link (VL) to meet service requirements. (d) The NS expansion to NFVI-PoPs is a use case to expand the NS over the two sites when workloads of the NS cross its capacity threshold. This dissertation describes the operational flow of each use case and the information exchanged between reference points in the NFV architecture to achieve these use cases.

This dissertation also proposes a scheme and the protocol extension for exchanging network information between providers. Prior to this proposal, the exchange of network information between providers has not been well-discussed, since the NFV use cases focus on a single operator case, which means that the NFV orchestrator (NFVO) can manage all network information. I detail the overloading issue of the existing protocol and propose a novel interoperable architecture among multiple Virtualized Infrastructure Managers (VIMs) for reducing the NFVO load. Additionally, practical issues including security and protocol extension are thoroughly discussed. My efforts on the request congestion management and multiple WAN connections represent an innovative solution for achieving the NS deployment across multi-provider networks. Suggestions on exchange parameters of L2 WAN connectivity and L3 WAN connectivity are introduced. My proposal was accepted into the ETSI NFV Release 3 specifications because it showed use cases involving networks from multiple providers, like we see with multihoming. This use case proposal also allows NFVO to manage multiple VIMs and overcome capacity limitations. The ETSI Group Report (GR) NFV- Interfaces and Architecture (IFA) 022 report analyzed these use cases in more detail and summarized suggestions for improving the existing specifications. My proposal finalized data model level (stage 2) specifications and discusses protocol level (stage 3) specifications.

Another critical component to meet service requirements is the selection of an appropriate network, as the network reliability depends on the operation of each network provider. This dissertation proposes a method that enables the lower and upper reliability to be computed in a distributed manner without requiring privacy disclosure. While this problem may seem similar to a traditional reliability evaluation assuming a single-domain network, the existence of multiple domains introduces the following challenges. One is the high computation complexity; i.e., network reliability evaluation is known to be #P-complete, which has prevented the reliability evaluation of multi-domain networks. The second is intra-domain privacy; i.e., network providers never disclose the internal data required for reliability evaluation.

I have proposed a method to partition the network size so as to yield upper and lower bounds of reliability. My method is solidly based on graph theory and is supported by a simple protocol that secures intra-domain privacy. My rigorous theory allows for an effective partition. The partition reduces the problem size to decrease the computation complexity. Additionally, the partition guarantees that no intra-domain information is disclosed. The theory utilizes the graph contraction technique to yield upper and lower bounds of reliability. I have defined a primitive protocol between service provider (SP) and domain providers (DPs). DPs can compute the reliability of their domains without revealing their internal data. The computed reliabilities are processed by the SP using secure computation techniques. Several practical issues including inter-domain connections are also addressed. Experiments on real datasets show that the method can compute the reliability for 14-domain networks with 907 links in one second. The reliability is bounded with reasonable errors; e.g., the bound gaps are less than 0.001 with high availability links of 0.9999. The privacy issue has not been studied in the long history of network reliability. This will be a key issue in the future of network services, since multi-provider network services have been recently discussed in the standardization bodies.

A feasibility evaluation is required to clarify the requirements for network path control scenarios of NS deployment across multi-provider network. This dissertation presents a dynamic network path control scenario with dynamic inter-domain and intra-domain network path control using optical switching and control plane technologies. The focus is inter-domain network path creation, Quality of Service (QoS) recovery for protecting high priority traffic transmitted over user network interface using policy controllers, and a failure recovery of Label Switched Path (LSP) established over external network to the network interface. Routing problems that arose in the multi-domain network were successfully solved and the actual service activation time of inter-domain Ethernet transport services between US and Japanese domains was evaluated. The QoS recovery successfully achieved the migration of high-priority video traffic between Tokyo and Osaka nodes in the Japan Gigabit Network (JGN) II network testbed with no confusion within about half a minute. There was no packet loss for high-priority traffic flow when migrating traffic between Multi-Protocol Label Switching (MPLS)-LSP and Optical LSP. This indicates that the proposed traffic control scheme can be applied to NSs that require QoS recovery within minutes with the low packet loss rates in multi-provider networks. The link failure recovery was also confirmed by using hierarchal LSP over the network testbed without the outflow of any control packets to an outside domain. The restoration time of the link failure recovery that I measured took 272 ms. These results show that the hierarchical LSP can perform link failure recovery without the outflow of any control packets to an outside domain and is effective in an actual operational requirement.

My efforts have revealed methods to exchange parameters between multi-providers and to assess network reliability across multi-provider networks. I believe that my work will open up new directions for research and development into end-to-end network service deployment across multi-provider networks to meet service requirements.

Form8・Separate Sheet
(様式8・別紙)

Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏　名　　谷口　篤

Title
論文題目　Dynamic network service control and management techniques across multi-provider networks

本論文は、クラウド／アプリケーションサービス事業者が複数事業者のネットワークを接続してサービスを動的かつ高信頼に提供するためのネットワーク制御・管理方式に関して出願者が行った研究内容をまとめたものである。近年のサーバやネットワークの仮想化技術の進展により、多様なサービスが複数事業者のネットワーク上の仮想化機能を連結して提供されており、ネットワーク全体としての高信頼性の確保が益々重要となってきている。複数事業者間のネットワークは現在では人手により静的に設定されており、サービス需要や要件に応じた動的なネットワークの設定・変更は困難であり、規模が拡大するとエンドエンドでの信頼性の評価が困難になるという問題があった。また、複数のネットワークの相互接続性の確保のためには国際標準化団体における仕様の標準化も必要である。本研究の目的は、これらの課題を解決するための全体アーキテクチャを国際標準化にも貢献しつつ見出すことであり、出願者は、複数事業者のネットワークを活用するユースケースを明確にしつつ、ネットワーク間接続のための情報交換、ネットワーク選択のための信頼性評価、ネットワーク設定の迅速性確保に関して研究を実施した。

論文は6つの章から構成され英語で書かれている。第1章では研究の背景と目的、ならびに複数事業者のネットワークによりサービスを提供する際の手順、信頼性評価、ネットワーク設定方式に関する既存研究と標準化動向について述べている。

第2章では、複数事業者のネットワークを活用するユースケースを国際標準化団体での提案をベースに記述している。出願者は、ネットワーク機能仮想化を推進している標準化団体 ETSI (European Telecommunications Standards Institute)の ISG NFV (Industry Specification Group for Network Functions Virtualization)のメンバであり、4つの基本的なユースケースを提案した。複数のネットワーク間で仮想化機能を疎通させるケース、リソース容量を一括変更するケース、サービス要件に応じてネットワークを選択するケース、サービス需要増に応じて一時的に他のネットワーク上に仮想化機能を増設するケースにおいて、必要とされるサービス機能とその配備方法、それらの機能を結合させるための手順、サービスの運用フローなどを提案し、ETSI NFV release 3 として採用された。

第3章では、複数事業者間でのネットワーク情報の交換方式に関して、ETSI ISG NFV での提案をベースに記述している。第2章のユースケースの実装例という位置づけであり、レイヤ2/3レベルでの接続における VLAN(Virtual LAN)、VPN(Virtual Private Network)、IP関連情報に関して、複数事業者間での負荷の軽減やセキュリティの確保などを考慮した情報交換方式を提案した。この方式についても、ETSI NFV release 3 仕様として採用された。

第４章では、大規模な複数事業者間ネットワークの信頼性を評価する手法を提案している。ドメイン間での情報秘匿を配慮しながら、複数事業者をまたがるネットワークのエンドエンド信頼性を求めるためのネットワークモデルを提案し、信頼性の上限値と下限値を求める定式化を行うとともに、実在する様々なネットワークに関する公開情報を用いてその有効性の評価を行った。従来手法では指数的に計算量が増加し6ドメイン程度で計算不可となるが、本提案手法では、14ドメイン、900以上のリンクを有するグローバルなネットワークにおいても、約0.1秒で計算可能であることを示した。

第５章では、複数ネットワークを跨るパスを動的に設定するための方式を提案している。複数ネットワークでのルート指定パラメータの明確化やパスの階層化を行い、実装置を制御するためのプロトコルソフトウェアを開発して、フィールド実験を行った。パスの動的設定に加えルート切り替え等の実験も行い、現在の人手を介する方式では２週間以上かかる設定を、提案・開発した方式により、グローバル環境でも数十秒程度で実現できることを示した。

最後に、第６章では本論文の内容をまとめ、今後の研究課題と展望を示している。

この研究の成果は、電子情報通信学会英文論文誌１篇、IEEE Communications Magazine １篇、査読付き国際会議論文２編として発表を行っている。

以上を要するに、本論文は今後益々利用が進む複数事業者間を跨ったネットワークサービスを動的かつ高信頼に提供するためのネットワーク制御・管理方式に関して、具体的なサービスを想定した情報交換方式を明確にし、具体的な構成を想定したネットワーク信頼性評価手法を提案して、その有効性を示したものであり、その学術レベルと実用的な意義は十分に高いと認められる。

以上の理由により、審査委員会は、本論文が学位の授与に値すると判断した。