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論 文 審 査 委 員	（主査） 教　授　村田　正幸 （副査） 教　授　村上　孝三　　教　授　今瀬　　眞　　教　授　東野　輝夫 教　授　中野　博隆

論 文 内 容 の 要 旨

The volume of the Internet traffic has been increasing rapidly due to the growth of the population of Internet users and the popularization of online applications and services that require high bandwidth, such as voice chat, video streaming, P2P file sharing, and grid computing. To accommodate the Internet traffic, the capacity of backbone networks has been enhanced by WDM (Wavelength Division Multiplexing). WDM is the technology that multiplexes and carries signals of different optical wavelengths in a single optical fiber. Although WDM resolves the shortage of the fiber capacity, the nodes connected to the WDM-capable fiber become the bottlenecks because those nodes must convert received signals between the optical format and the electric format and process the signals at the speed of light. Therefore, WDM-based networks are extended to wavelength-routed networks by installing optical switches in the nodes. Wavelength-routed network is based on the circuit-switching paradigm; nodes are connected with dedicated virtual circuits called lightpaths. By configuring lightpaths, a logical topology is constructed over a wavelength-routed network.

A wavelength-routed network consists of data plane and control plane. Lightpaths are established on the data plane including optical switches and fibers while those lightpaths are controlled in the control plane. There are two standard control architectures for wavelength-routed networks, GMPLS (Generalized Multi-Protocol Label Switching) and ASON (Automatically Switched Optical Network). These architectures have been being designed so as to interconnect multiple wavelength-routed networks. The progress of the standardizations of these architectures grows the scale of wavelength-routed networks. As a result, large-scaled wavelength-routed networks are comprised. Due to this enlargement, the volume of the traffic carried over the networks increases. The probability that a network failure occurs gets higher because of the increase of the number of network components. In addition, the amount of the information for managing

networks also increases. Hence, flexibility, reliability, and scalability are serious issues for large-scaled wavelength-routed networks.

In this thesis, we propose a method to reconfigure logical topologies to retain the flexibility of wavelength-routed networks, at first. A lot of logical topology design algorithms have been proposed in previous studies. In these studies, most of those algorithms commonly assume that the traffic demands are known in advance. In spite that, as the network scale gets larger, the volume of traffic grows and the traffic pattern changes. To accommodate the increasing and changing traffic, the current logical topology should be reconfigured to a new optimal logical topology. The new logical topology can be obtained by using any of the logical topology design algorithms, but the traffic carried over the working lighptaths are lost since those lightpaths are torn down to setup new lightpaths. Hence, we develop a reconfiguration method diminishing the traffic loss during reconfiguration. The results of simulations show that our method can reconfigure logical topologies without traffic loss.

We next focus on the property of the physical topologies of large-scaled wavelength-routed networks. The scale of wavelength-routed networks grows by interconnecting a lot of small wavelength-routed networks. The Internet has also been growing in the similar way; by interconnecting ASes (Autonomous Systems). In addition, it is known that the topology of the Internet has power-law property on its degree distribution. In the topology having the power-law property, there are a few nodes that have lots of links (called hub nodes) while most of the other nodes have only a few links. According to the analogy of the growth of the Internet, it is speculated that the topologies of large-scaled wavelength-routed networks also have the power-law property. In such networks, the hub nodes are likely to be the bottlenecks of the resource utilization since a lot of wavelength requests conflict at those nodes. As a result, a number of wavelengths are required to accommodate the traffic although there are available wavelengths at non-hub nodes. Hence, we introduce the concept of virtual fiber and propose a wavelength routing method to distribute the load on the hub nodes. We construct logical topologies over physical topologies by configuring virtual fibers. Then we route lightpaths in logical topologies, not in physical topologies. By adopting our method, performances of WDM networks with the power-law connectivity are improved without any cost for network equipments and link state based routings. We evaluate our method by computer simulations and the results show that our method reduces more than one order of magnitude of blocking probability.

The information about lightpath management is exchanged among nodes using a certain signaling protocol. Signaling protocols are classified into two classes ; soft-state and hard-state. In soft-state signaling, the reservation states at each node are managed with timeout timers and periodic refresh of the reservation states are required to keep them. If the timer is expired, the corresponding reservation state is deleted; that is, the reserved wavelength is released. On the other hand, hard-state protocols manage the reservation states explicitly with control messages. Although the number of control messages of soft-state signaling is greater, this timeout mechanism is significant especially for large-scaled networks. This is because the mechanism guarantees the release of the reserved wavelengths even if release messages cannot be delivered due to message losses or control channel failures. In hard-state signaling, if the message to release a reserved wavelength do not reach the destination node due to message loss or control channel failure, the reservation state becomes orphaned and the wavelength to be released is kept reserved. Soft-state signaling protocols have some control parameters but the effects of tuning those parameters are not understand well. Therefore, we analyze the performance of soft-state signaling using Markov model. We also evaluate the effect of the message retransmission extension for signaling protocols with various parameters. As a result it is revealed that soft-state signaling with the message retransmission extension would reserve a wavelength uselessly about 10 times as long as soft-state signaling without the extension when there are 1000 sessions at a node.

We finally introduce a local recovery scheme against multiple node failures in a certain region of a network (we call them massive failures). Massive failures would be caused by natural disasters, such as earthquakes, or by power-cut. There are a lot of studies on protection of lightpaths against a single node or link failure. However, when it comes to a massive failure, such protection schemes using backup lightpaths are ineffective since the backup lightpaths would also be failed. In addition, it is difficult for remote nodes to know the exact failed place in large-scaled networks. Therefore, the performance of the end-to-end recovery is degraded. In contrast to this, our proposed scheme locally configures a cycle enclosing the part of a massive failure, called diverting cycle. Then, disrupted lightpaths are diverted along the diverting cycle. Our recovery scheme also reduces the amount of control messages since a huge number of control messages are exchanged for failure notification, link-state update, and lightpath recovery after a massive failure. The results of computer simulations show that our scheme recovers the lightpath connectivity to almost 100% more quickly than the path restoration scheme when the scale of massive failures are not large. When the scale of massive failures are large, our scheme reduces the number of control messages to about the half, comparing to the path restoration scheme.

論 文 審 査 の 結 果 の 要 旨

バックボーンネットワークとして使用される波長ルーティングネットワークは、光ファイバと光スイッチからなり、特定の光波長を用いて光パスと呼ばれる回線を設定して通信を行う。波長ルーティングネットワークは回線交換方式によって通信を行うため、トラヒックの変動に対する資源利用の柔軟性が求められる。また、バックボーンネットワークとして、障害に対する高い信頼性が要求される。今後、波長ルーティングネットワークは、その普及に伴い大規模化するため、拡張性も不可欠である。

学位申請者はまず、波長ルーティングネットワークのトラヒック変動に対する柔軟性について考えている。波長ルーティングネットワークでは、トラヒックの分布に応じて光パスを設定し、論理的なトポロジを構成する。トラヒック分布が変動すると論理トポロジを再構成するが、既存の手法では再構成中にトラヒックを損失する。そこで、学位申請者はトラヒックを損失せずに論理的なトポロジを再構成する手法を提案している。ネットワークを運用するキャリアにとってトラヒックの損失は最も避けるべき事態の一つであり、従って、学位申請者の提案する再構成手法の有用性は非常に高い。

次に、学位申請者は大規模な波長ルーティングネットワークの拡張性に注目している。大規模な波長ルーティングネットワークのトポロジではハブノードと呼ばれる出線数の多いノードが出現すると予測される。学位申請者はハブノードの存在によって波長資源の利用効率が低下することを示している。また、ハブノードの影響を緩和し、資源の利用効率を改善するルーティング手法を提案し、光パス設定の棄却率を1桁以上改善できることを示している。将来的な波長ルーティングネットワークの拡大を見据え、そのトポロジ特性を考慮した研究は皆無であり、その新規性は高く評価できる。

波長ルーティングネットワークでは、シグナリングプロトコルに従って光パスが設定される。RSVP-TE はそのシグナリングプロトコルであり、現在標準化が進められている。しかし、RSVP-TE で用いる複数の制御パラメータと資源の利用効率の関係は未だ不明である。そこで、学位申請者は RSVP-TE の制御パラメータと資源の利用効率の関係を解析的に示している。また、1 ノードに 1000 本程度の光パスが通過するような大規模なネットワークでは、RSVP-TE の性能向上のための拡張機能の一つが、むしろ性能を低下させる可能性があることを示している。この結果は、今後のネットワーク設計の指針として有用である。

波長ルーティングネットワークに関する従来研究では、ある領域内で同時に発生する障害は考慮されていなかった。このような障害（以下、面障害）は地震や電力供給障害などによって引き起こされるが、従来の障害回復手法は、面障害を想定していないため適用できない、若しくは適用してもその効果が十分に得られない。そこで学位申請者は面障害にも対応できる障害回復手法を提案している。提案手法は光パスの経路長に依存せず高速な障害回復ができる。また、従来手法に比べ、制御メッセージ量を約半分に抑えることができ、障害回復時のネットワーク制御部の輻輳を回避することができる。これは大規模な波長ルーティングネットワークの信頼性向上に対して大きく貢献すると考えられる。

以上のことから、博士（情報科学）の学位論文として価値のあるものと認める。