論文要旨

Reconfigurable optical add/drop multiplexers (ROADMs) were demonstrated in our laboratory for use in IP-over-CWDM (Internet Protocol over coarse wavelength division multiplexing) networks. However, it has a fixed number of wavelength reconfiguration capabilities. In order to remove this limitation, and to keep the initial network cost low, stackable ROADMs (S-ROADMs) have been proposed for use in IP-over-CWDM networks in this dissertation. The S-ROADMs provide the capabilities of remote lightpath reconfiguration as well as the manual ROADM reconfiguration under the best-effort transmission specified by the service level agreement (SLA). The S-ROADM can be constructed by connecting modules with different wavelengths required in the node. This feature decreases the initial network cost. When an S-ROADM is reconstructed by adding the required wavelengths, it is referred to as manual ROADM reconfiguration. The experimental results clarified that the S-ROADM could multiplex and demultiplex the wavelengths successfully, and gave no limit to the passing-through wavelengths, making the network be wavelength transparent. The performance of the S-ROADMs was evaluated by removing congestions by adding new lightpaths remotely in an IP-over-CWDM network. Manual ROADM reconfiguration was also done on the in-service network and the performance was also satisfactory enough to meet the requirements for the best-effort transmission specified by the SLA. A stackable module with a bidirectional CWDM amplifier has also been proposed to introduce the optical amplifier into an S-ROADM for use in an IP-over-CWDM ring network with longer distance, and the performance was evaluated experimentally. The respective results in each chapter are summarized as follows.

Chapter 2: The structures of the stackable ROADMs for both unidirectional and bidirectional

transmissions have been proposed and described clearly. The physical properties of the S-ROADMs clarified that the S-ROADM could multiplex and demultiplex the wavelengths successfully, and did not limit any passing-through wavelengths, making the network be wavelength transparent. The possible transmissions for one wavelength are explained, and it is found that three types of connections are possible by the S-ROADM. The S-ROADM consists of some modules and each module can reconfigure one wavelength. Therefore, only necessary wavelength's module can be installed in the S-ROADM, ensuring other wavelengths to be passed through. Loss equations for all kinds of connections are also presented. Finally S-ROADM with 3-port components is also proposed and explained at the end of chapter 2. The merits and demerits of three types of S-ROADMs are also discussed.

Chapter 3: In order to examine the congestion removing performance of the S-ROADMs, a 5-node experimental network was constructed. The lightpath reconfiguration was done for removing the traffic congestions. The congestion removing performance by the S-ROADMs was evaluated, focusing on the recovery time to keep throughput given by SLAs. It is assumed in this thesis that IP packets are routed by open shortest path first (OSPF), i.e., the packets are transferred through the physical layer lightpaths, according to the routing tables created by OSPF in the layer 3 switches (L3SWs). Therefore, the routing tables are changed dynamically so as to transfer packets by the shortest path between the nodes, when lightpaths are reconfigured. Therefore, there are 2 possibilities that the traffic congestions are removed in a network. One is IP routing reconfigurations changing the routing tables such that some of the streams sent through the congested route are transferred to a bypass route, i.e., by adding a static bypass route in the non-congested lightpaths between the source and destination nodes. Another way to remove the congestion is the lightpath reconfiguration by the S-ROADMs to add one or more new lightpaths to the congested route.

In both of the methods, the amount of traffic transmitted through the congested route was divided into two streams. First stream S1 was set to be a little below the capacity of the lightpath, and the second stream S2 was set to be the excess traffic that caused the congestion. The congestion was removed, after the routing for S2 was changed so as to send S2 through a bypass route. The static bypass route was created through other lightpaths between source and destination nodes in the network, 3 s after the control and configuration signals were sent, i.e., the S2 was transmitted through the static route created via the bypass lightpath, In another case to add a new direct lightpath, S2 was transmitted through the newly added direct lightpath. It took 8 s to remove the congestions after the control and configuration signals were sent. The congestion degraded the throughput but the congestion related time was smaller than the value specified by the SLA, Thus, the S-ROADM satisfied the SLA for best-effort type networks.

The ROADM reconfiguration was also done in the network, and the performance was evaluated. When new users require services in the network, and no bandwidth can be allocated to the users by the existing lightpath set or by reconfiguring the lightpaths, the ROADM reconfiguration can be done in the proposed S-ROADM as explained above. The ROADM reconfiguration is made by adding a stackable module manually to the in-service S-ROADM to make more lightpaths available in the network. When adding the module, the fibers are disconnected, which causes transmission breaks, and the module is inserted between them. Generally, networks are designed so as to be protected, when a failure occurs, by giving a bypass route. In ring networks, the clockwise route is used as the bypass route, when the counter clockwise route fails, and vice versa. During the ROADM reconfiguration, the bypass route can be used, but the issue to be investigated is how long it takes to recover the breaks in the in-service network. After the ROADM reconfiguration started, some of the lightpaths associated to the disconnected fiber were disconnected in the network, and the associated packet streams disappeared. The packet streams appeared, again, in 6.5 s through the bypass route. It is understood that it took 6.5 s for OSPF to find and establish

the bypass route. Here, the hello and dead intervals were set to be 1 s and 4 s, respectively. The routes are changed again 10.1 s after the disconnection of the fiber, so as to transfer the lost packet streams through the original direct routes. This is because the module addition to the S-ROADM was completed, and OSPF found and established the shortest paths. In all the cases, the performance satisfied the SLAs.

Chapter 4: A stackable module with a bidirectional CWDM amplifier has also been proposed to introduce the optical amplifier into an S-ROADM for use in an IP-over-CWDM ring network, and the performance was evaluated experimentally. Packet transfer changes were monitored during the lightpath reconfigurations, including the lightpaths which needed optical amplifications. The result clarified that the lightpaths were reconfigured successfully, including the remote activation of the amplifiers. As a result, the stackable feature of the amplifier module enables us to provide the cost-effective introduction into the network on an *implement-it-when-necessary* based service in a fully compatible way with other stackable ROADM modules, when constructing the S-ROADM with an amplifier. Therefore, the amplifier module can be used in the same way as the stackable modules to construct the S-ROADM. Thus, the amplifier module has a big advantage to use it flexibly and economically in the IP-over-CWDM networks.

審査結果の要旨

本論文は、大規模 LAN (Local Area Network)やキャンパスネットワーク、地域ネットワークなどのブロードバンド光 IP（Internet Protocol）ネットワークにおいて、トラフィックの輻輳が生じたときに光パスの再構築により輻輳を解除する ROADM (Reconfigurable Optical Add/Drop Multiplexer)に関するものである。従来の ROADM が固定波長対応であったのに対し、モジュール型の Stackable ROADM (S-ROADM)を新しく提案し、モジュールを追加することで波長を柔軟に追加できる構造とし、その有効性を実験的な検討により明確化したものである。得られた主な結果は、以下の項目に要約できる。

(1) CWDM (Coarse Wavelength-Division Multiplexing) 対応の ROADM として、従来の波長依存性のカプラ、スプリッタと光スイッチから成る構造に替り、波長ごとに OADM と光スイッチから成るモジュールを基本単位とし、これを接続して成る S-ROADM を提案した。従来型が通過波長数に制限がある固定波長であるのに対し、提案した S-ROADM は波長制限がなく、波長透過性を有することから、拡張性に優れる。S-ROADM からなる光 IP ネットワークにおいて、1 か所の制御システムから遠隔制御により、S-ROADM の光スイッチを制御し、光パスを再構築できることを明確にした。

(2) S-ROADM からなる光 IP ネットワークにおいて、輻輳の解除法として IP ルーティングを再構成する手法と、S-ROADM により光パスを再構築する手法を検討し、いずれの手法でも輻輳を解除できることを明確にした。前者は、1 つの光パス内のトラフィックを別ルートに変更するもので、小さな粒度のトラフィック平準化に対応し、光パスの再構築は1 つの光パスの容量単位の平準化に対応する。2 つを組み合わせることで効率的なトラフィック平準化が可能である。

(3)長距離の光パスに対応できるよう、光アンプを S-ROADM に導入するアンプ付モジュールを提案し、他のモジュールと完全互換で S-ROADM に光アンプを組み込めることを明確にした。また、光パス再構築時に光増幅が必要な場合、光増幅を行って S-ROADM が動作することを実験的に明確にした。

以上の結果は、光 IP ネットワークを広く適用する上で必要となる技術を進展させており、本分野の学術および産業上の発展に寄与するところ大である。また、申請者が自立して研究活動を行うのに必要な能力と学識とを有することを証したものである。

学位論文審査委員会は、本論文の審査ならびに最終試験の結果から、博士（工学）の学位を授与することを適当と認める。