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論文要旨

Over the past decade, the Internet has become one of the most used media for communication. As a result, the network traffic is growing year after year, what is a motivation for researchers to improve technologies related to data transmission, like network architectures or transmission protocols. The main goal is to make a better use of actual resources, and thus increase the global capacity of the networks. Nowadays, optical fibers are one of the best choices to do so. Being reliable, fast, small and light, they can provide enough bandwidth for our actual need. The strength of fibers is to be able to carry many wavelengths to transport data simultaneously. Current research is still developing what is called Dense Wavelength Division Multiplexing. This technology allows us to support over one hundred wavelengths in a single fiber. Concurrently, a single wavelength is able to reach over 100 Gbps. Those two characteristics, combined, have a large influence in the research field. Concerning optical network technologies, one of the most investigated subjects is the way of switching data. Three principal paradigms have been considered until now: Optical Circuit Switching (OCS), Optical Packet Switching (OPS) and Optical Burst Switching (OBS).

Like old telephones before VoIP expansion, OCS needs an end-to-end connection before starting data transfers. Precisely, along the path between the source and the destination, all optical fibers set aside a wavelength for a particular transmission. If a reservation cannot be made, the communication establishment is rejected. End-to-end lightpath establishment is what ensures

OCS to be the most reliable switching technology for long transmissions. The main drawback is that since wavelength resource is limited, keeping holding a long time an end-to-end connection increases the rejection probability of other lightpath establishments. The more wavelengths are needed, the more the rejection probability increases. This network is consequently great for large file transfers or light traffic load, and poor when fine granularity is required, especially in the case of the Internet, where the size of transfer units is commonly 1.5 KiB (packet size).

Unlike OCS, OPS reserves a wavelength between two successive nodes just before forwarding a packet instead of establishing end-to-end lightpath. When a packet reaches a node of the network, control information is extracted, processed and then reinserted in the packet when a new forwarding output link is reserved. During that processing period, data part of the packet is buffered in the node using a Fiber Delay Line (FDL), which virtually lengthens the distance traveled by the wave. Nonetheless, actual fiber delay lines are expensive and cannot retain the wave for a long time in a server (few nanoseconds). This lack of efficient optical RAM implies that if a new subpath cannot be reserved in time, the data packet is dropped from the network. A new transfer is consequently needed from the source. That blocking probability is really problematic and implies, as a consequence, a bad use of the network bandwidth. OPS is conceptually a promising network, but for a far future.

In the case of OBS, packets are assembled together before transmission to create a burst, which becomes the minimal transfer unit of the network. Thanks to that, the network globally needs less wavelength reservations than in the OPS case. A control message is sent before the data transfer through a special communication line in order to reserve the lightpath. After an offset delay time, the data burst can be sent, following the path reserved by the control packet. Hence, OBS does not need buffering or just a few. Unlike OCS technology, wavelengths are reserved only for a small amount of time and can be released just after a burst is switched (Just-Enough-Time signaling). This leads to finer granularity than OCS and a better utilization of wavelength bandwidth. If the reservation process is too slow, the burst will reach the node where reservation is happening. In that case, the burst is quickly dropped. Burst loss is a critical topic to be solved in OBS networks, because the TCP layer is not able to well interpret a burst drop: this could set off congestion avoidance algorithms, and slow down the network at awkward moments. Even if contention avoidance techniques like Predictive Bandwidth Reservation ones can reduce burst loss, they are not efficient enough to allow the deployment of such a network. The concept of burst is still attractive to lighten the traffic load of packet-based networks.

Future networks will have to face a traffic explosion due to, for instance, the transmission of ultra high definition videos (4K, 8K) or the next-generation 3D and holographic imaging. All-optical solutions have been proposed to provide very large capacity networks able to deal with such a demand. However, the state-of-the-art device technology is not mature enough to provide these attractive solutions. Translucent networks, allowing optoelectronic conversions at some points of the network, are now considered as the most viable solutions. In these networks, it is essential to minimize the amount of optoelectronic conversions. This problem is usually related to the knowledge of *where* conversions should be achieved in the network. As for the transmission of huge contents, two main applications can be distinguished, each one using a different kind of network. The first one is streaming. Since it is a real-time application, circuit-switching is classically preferred for keeping a high Quality of Service. The second one concerns data exchange (between data centers for instance). In such a case, packet-switching is desirable. Conventional hybrid network solutions consist of a circuit-switching plane and a packet-switching plane in order to deal with both applications. Nevertheless, the network must decide through which one of them a content will be transmitted before the transmission. This rigid separation is not effective enough to deal with the increasing demand and the massive fluctuations of the forthcoming traffic.

This thesis proposes a hybrid network, called Content-based Switching Network (CSN), which can be considered as a fusion of Optical Circuit Switching and Store-and-forward based networks (i.e. allowing intermediate buffering). Unlike the aforementioned clear plane separation solutions, each one of the CSN nodes has the capability of flexibly choosing its switching paradigm for a specific transfer, depending on its status, and reserves the resources accordingly. Switching paradigms are optical bypass, electrical bypass, and store and forward. This leads to a network which is able to dynamically adapt itself to the demand.

The main benefits of the proposed network are as follows. Under low traffic load condition, CSN can use a circuit-switching approach for all contents, which is the best if resources are available, leading to a better use of the resources of the network. Under higher traffic condition, each node can perform an optoelectronic conversion on the fly for a specific content if needed (resource shortage, physical impairments), solving the questions of *when* and *where* a translucent bridge should be made. This virtually maximizes the merit of the optical transmission, in contrast to usual packet-switching networks which forcibly buffer the content at each node while the header is checked, introducing undesirable latency. From the viewpoint of service provisioning, real-time capabilities are fundamental; for instance, for online games or video on demand services. If a specific content does not require these capabilities, CSN can provide delay tolerant services if needed. Finally, since in CSN a content is always transferred in one piece, the user does not need to worry about cumbersome packet interleaving.

As for the content of the thesis, it is organized as follows.

Chapter 1 essentially gives an extended summary of the thesis. Significant differences between various optical solutions are briefly described. Hybrid networks, which implement a rigid switching plane separation, are also introduced. The Content-based Switching Network, which addresses the issues inherent to conventional hybrid networks which implement a horizontal separation over the entire network (from edge to edge), is proposed.

Chapter 2 gives background explanations in order to fully understand the benefits of the Content-based Switching Network. The content of this chapter is mainly focused on the introduction of different network solutions. For clarity, the description of basic devices which are not directly related to the subject of this thesis is avoided. This chapter is organized as follows. First, a basic model of optical network that is used in this thesis is proposed. Then, a technology called Wavelength Division Multiplexing, allowing the simultaneous transfer of several contents in one fiber is introduced. Several switching paradigms as well as their technology are also described. Various basic network solutions, which are OCS, OPS and OBS, are described, including their architectures and their signaling schemes. Two different sorts of hybrid networks are presented. Finally, the proposal of this thesis, the Content-based Switching Network, is succinctly described. After that, a comparison between CSN and the other technologies is made in order to stress its differences and its merits.

Chapter 3 gives the description of the Content-based Switching Network, its deployment, and simulation results. A global description of the network is given. It includes its signaling scheme and switching paradigm selection in core nodes, the description of access and core nodes, the introduction of timeouts which allow the network to safely drop contents, the details concerning a dynamic wavelengths attribution mechanism, and finally a procedure that was designed in order to deal with the synchronization issues of the signaling. CSN possible applications, extensions and deployment are tackled. Various simulation results are given, showing the superiority of CSN over an OCS network. Also, a specific scenario concerns the progressive deployment of CSN over an existing OCS network.

In Chapter 4 gives more technical details concerning how the CSN signaling works in order to be able to implement it. Information carried by the control messages as well as their kinds are listed. The core nodes statuses, which depend on the reserved resources and the kind of switching paradigm used, are given. Control message processing is detailed from both the viewpoints of the access and the core nodes.

Chapter 5 finally concludes this thesis.

審査結果の要旨

本論文は，様々な種類の大容量通信を伝送・交換することができる将来のネットワークアーキテクチャの確立を目的として，これまで個別に研究開発が進められてきた光回線交換網，光パケット交換網，光バースト交換網などの将来ネットワークに対し，それらをコンテンツ転送という視点から統一的に扱うことが可能な新たな光・電気融合ネットワーク基盤を提案し，詳細設計を行うとともに，その有効性の検証について研究したものであり，以下の成果を得ている.

(1) 全光の交換処理ではなく，特定の中継ノードで光電変換を伴うトランスルーセント（半透明）な光ネットワークにおいて，転送コンテンツのサイズと各中継ノードにおける波長・メモリなどのネットワーク資源の利用状況に基づき，光電変換処理及び蓄積転送処理を行うべき必要最低限の中継点を自律的に決定する制御を確立し，そのシグナリング規律を設計した．また，計算機シミュレーションによる性能評価を通して，各種交換原理を統一化した提案方式により，コネクションの接続成功率が向上することを定量的に明らかにした.

(2) 転送対象である情報（コンテンツ）を一体として伝送するという斬新な原理を導入し，情報転送の単位をパケット，部分ファイル，完全ファイル，複数ファイル集合など，任意に設定可能とすることにより，従来の TCP/IP ネットワークにおける情報の細断に伴う不到達問題や順序逆転問題，部分再送問題などの複雑性を原理的に解消できることを示唆した.

(3) 送受信ノード間距離が離れた通信に対して，特に接続成功率が低下するという接続品質の不公平性問題に対し，優先利用波長領域を導入し，適応的にその優先領域を変更することにより，長距離大容量伝送の要求に対する接続成功率を向上させ，公平な接続品質を達成した.

(4) 提案ネットワークの普及問題に焦点を当て，現状の光回線交換網に対し，提案アーキテクチャに従う新規ノードを部分導入した場合の性能を接続要求に対する失敗率の面から定量的に明らかにした．具体的には，適切な負荷領域で 60％の新規ノード普及率の場合，導入しない場合に比べて 1/10 の接続失敗率，100％普及率の場合には，1/100 の失敗率を達成することを明らかにした.

以上の諸成果は，全光ネットワークへの進化を志向した新世代光ネットワークのあり方について重要な知見を与えるものであり，本分野の学術的・産業的な発展に貢献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を有することを証したものである.