# 論文の内容の要旨

論文題目　**Design and Implementation of a Burst-Switched Photonic Network**

（光バーストスイッチネットワークの設計と実装に関する研究）

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The remarkable growth of Internet traffic has been requiring a high processing speed beyond a traditional electronic routers' capability with the power, weight and size scaling limitations. Meanwhile, rapid advances in wavelength division multiplexing (WDM) technology have provided a huge raw transmission bandwidth. The serious mismatch between the transmission capacity of optical fibers and the routing/forwarding capability of electronic routers has been driving the evolution of Internet architecture to an IP-centric optical switching network, called optical Internet. In this scenario, the optical technology is expected to play a stronger role not only for transmission but also for switching. Up to now, many research activities have been focused on three optical switching technologies: optical circuit switching (OCS), optical burst switching (OBS), and optical packet switching (OPS). OBS is considered an attractive switching paradigm because it is more efficient than OCS in terms of wavelength utilization efficiency and has less stringent requirements for optical devices than OPS.

OBS attempts to address the problem of efficiently allocating resources for bursty Internet traffic. In OBS, data is forwarded in optical domain while routing/forwarding decision is made in electronic domain using one-way resource reservation protocol. More specifically, incoming data is assembled into bursts at the edges of the network, and the burst is sent out following its control signal with an offset time without having to wait for reservation acknowledgement. The offset time allows intermediate nodes to complete control signal processing and optical switch configuration ahead of the burst arriving. By reserving resources only for the duration of the burst, high bandwidth utilization efficiency can be achieved in such networks.

Since burst transport is in the one-way connectionless manner and optical random access memory is not yet available, packet loss rate increases compared with that in conventional IP networks. Therefore how to provide reliable packet delivery over OBS networks is a major concern. On the other hand, since many key issues of OBS have been extensively studied in literatures, a practical OBS network platform is immediately needed to investigate their usability, evaluate their performances, and explore their future directions.

The objective of this dissertation is to address design and implementation issues for burst-switched optical networks. It aims to design a flexible node architecture and implement a set of efficient control protocols based on currently available and emerging technologies. Moreover,

reliable packet delivery mechanism is also our goal. The dissertation consists of three parts. In the first part, we present the design and discuss the implementation of an overlay mode optical burst-switched network testbed, including design principles, node architecture, and control protocols. In the second part, experimental results, including functional verification, performance evaluation, and application demonstration are discussed. In the third part, we propose a reliable transmission control mechanism over OBS networks. It is realized based on burst-level forward error correction (FEC), thus making packet delivery tolerable to burst contention.

## I Design and Implementation of an OBS Network Testbed

In this part, we study the design and implementation issues for an optical burst-switched network testbed. Unlike the previous OBS prototypes and testbeds that mainly focused on some key unit technologies, such as optical switches and signaling protocols, we designed and implemented a general-purpose and flexible OBS network testbed to provide a real network-wide evaluation platform. Detailed design principles include: (i) compatibility and interoperability with IP networks, which are achieved by asynchronous variable-sized burst switching performed on an overlay network model; and (ii) generality, modularity, and expandability, which are achieved by modular node architecture with transparent burst switching and reprogrammable control protocols. Guided by these principles, smart edge node and simple core node were designed and implemented, and efficient control protocols were developed.

### 1. Node Architecture Supporting CoS and Wavelength Selection

In many previous works, edge nodes only perform burst assembly/disassembly at the boundary of OBS networks. To support various network topologies and provide more intelligence, however, we propose a flexible "transceiver + forwarding" architecture for edge nodes to forward cut-through bursts, as well as perform burst assembly/disassembly with support for class of service (CoS) and wavelength selection. Such node architecture consists of an optical switching unit, a burst transceiver unit, and a control unit.

The key point of designing the optical switching unit is how to implement a high-performance transparent optical path with considerations of optical device limitations and physical-layer constraints. This goal is achieved by commercial high-performance optical devices incorporating carefully designed control circuits. Among them, optical switch and power imbalance are two crucial concerns. Considering speed, scale, and reliability, commercial planar lightwave circuit (PLC) switches were adopted to construct a $16\times16$ non-blocking switch matrix. The switching speed is less than *3 ms* and the insertion loss is less than *8 dB*. In OBS networks, power imbalance occurs not only between different links and wavelengths but also within each wavelength because bursts within a wavelength maybe come from different sources and go through different nodes and paths. We designed a dynamic channel-level power equalization scheme to compensate for power fluctuations, which was implemented with a variable optical attenuator (VOA) array and a corresponding feedforward control circuit.

The design focus of the burst transceiver unit is how to efficiently and flexibly support CoS and wavelength selection. A novel "3-level FIFOs + 2-level switch" burst transmitter architecture is proposed and implemented with an Altera high-end FPGA. The three-level first-in first-out buffers (FIFOs) are used for routing, burst assembly, and scheduling. The first-level switch classifies burst queues by destination and CoS, while the second-level switch executes wavelength selection. All the wavelengths can be shared for any burst, which makes the edge node flexible in supporting various wavelength assignment algorithms.

### 2. Control Plane with One-Way Signaling and Contention Resolutions

We present an OBS control plane model to show the relationship of control protocols and algorithms, including routing, scheduling, signaling, assembly, and disassembly. Implementation methods of control signal, multilayer routing, and one-way signaling protocol are described. In particular, we discuss a carefully designed burst scheduling algorithm that efficiently combines two contention resolutions: deflection routing and priority-based wavelength assignment (PWA). The deflection routing approach provides a detour path for a contending burst. With PWA, each node tends to assign the highest-priority wavelength to the burst, where every wavelength is dynamically prioritized for each destination by learning from its utilization history. Another feature of this scheduling algorithm is that it takes advantage of electronic buffers within the edge node. If there is no wavelength is available for a locally generated burst, the burst will be buffered for a short time and re-scheduled again, thus reducing blocking probability.

## II Experimental Study of Burst-Switched WDM Networks

Focusing on proof-of-concept, performance evaluation, and prospect investigation, the self-developed OBS testbed is evaluated and discussed in this part. Furthermore, in order to study the feasibility and performance of OBS under different technical conditions and network environments, experiments on another large-scale OBS network are also introduced.

### 1. Evaluation and Discussion of the OBS Network Testbed

The self-developed OBS testbed is evaluated and discussed. Firstly, by measuring optical burst, wavelength spectra, and burst forwarding procedure, we verified the feasibility of OBS, and confirmed that all functional modules work well as designed. Then, performances of OBS testbed, including end-to-end delay, burst blocking probability and TCP throughput, were evaluated and discussed. Finally, TCP/UDP-based online video services were demonstrated on the testbed. Experimental results indicate that the burst assembly, optical switching, and contention resolution are three key determinants of OBS performance. The corresponding improvement solutions and future research directions are discussed.

### 2. Experiments on an OBS Network Utilizing PLC and MEMS Switches

Not be limited to the self-developed OBS testbed aforementioned, experimental study is also extended to another large-scale OBS network testbed utilizing PLC and MEMS switches. On this testbed, the feasibility, effectiveness and application of PWA were demonstrated. In addition, performances and applications of two-way and one-way signaling schemes were analyzed and compared. Two-way signaling may be desirable for LAN and MAN applications under current technical condition. However, one-way signaling is expected to outperform two-way signaling in the future, especially for backbone network.

## III Reliable Transmission Control Mechanism over OBS Networks

Burst contention leads to packet loss, retransmission and accordingly high latency, thereby decreases the network performance. Related works on reducing burst contention include optical buffering based on fiber delay line (FDL), deflection routing, wavelength conversion, and burst segmentation. However, none of them can provide cost-effective and sufficiently low burst loss rate in a wide range of traffic load, especially in moderate-to-high traffic load. Unlike these previous works, we propose a reliable transmission control mechanism based on burst-level FEC, which makes the packet delivery tolerable to burst contention. The related key issues, including FEC-based burst generation, are described. Simulation results show that this mechanism can achieve sufficiently low packet loss rate in low-to-moderate traffic load. In addition, a loss-adaptive redundancy control policy and other implementation issues are also discussed.

### 1. Burst-Level FEC

At the ingress node, implementation of the burst-level FEC is divided into two steps: burst assembly and FEC encoding. In the first step, multiple incoming packets with the same egress address are assembled into a group of bursts, so-called burst-group with a total length of $p \times L$, where $p$ is the number of bursts contained in the burst-group and $L$ is the length of the burst. In the second step, FEC encoding is performed to the burst-group. Encoded burst-group consists of $n$ bursts, where $n>k$ and $k$ is the number of bursts required to reconstruct the original packets. At the egress node, once $k$ bursts (any combination in any order) are received, the original packets can be reconstructed.

### 2. Performance Evaluation

We evaluate the effectiveness of the burst-level FEC scheme by computer simulation. Simulation results show that by selecting suitable FEC redundancy and burst-group size, the proposed scheme can achieve sufficiently low blocking probability especially in low-to-moderate traffic load. Since fixed FEC redundancy usually leads to unnecessary bandwidth waste in the case of low loss rate, or decreases reconstruction probability in the case of high loss rate, a dynamic redundancy control policy is expected to overcome this disadvantage, where FEC redundancy can be dynamically adjusted according to network state, such as burst blocking probability.

## Future Works

The self-developed OBS testbed is the first implementation and demonstration of a network-wide testbed with comprehensive OBS functions. Experimental results show that the burst assembly, optical switching, and contention resolution are three key determinants of OBS performance. With the dramatic advances in optical and electronic technologies, we can expect that the former two can be greatly improved in the near future. For the third one, we plan to study the adaptive burst-level FEC coupling with congestion control. Another work is to consider the placement of wavelength converters together with the proposed transmission mechanism. Finally, how to realize quality of service (QoS) differentiation is also an attractive research direction.