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Performance evaluation of all-optical label swapping nodes

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RESUMEN DEL PROYECTO

El crecimiento incesante del tráfico en redes como Internet está forzando el desarrollo de técnicas basadas en IP que permitan aumentar la velocidad, capacidad, rendimiento y tasa de envío de paquetes. Más del 50% del tráfico IP está formado por paquetes menores de 522 bytes y la mitad de estos paquetes se encuentran en el rango de 40-44 bytes. Para llevar a cabo el encaminamiento de estos pequeños paquetes a tasas de Gigapackets/s se requieren tecnologías de de envío y encaminamiento que sean capaces de soportar los nuevos protocolos basados sobre IP como MPLS (Multi-Protocol Label Swapping), que simplifiquen la búsqueda de la ruta a seguir y separen las funciones de envío de paquetes de su encaminamiento. Desde hace tiempo las redes ópticas se consideran una solución viable a este problema dado su elevado rendimiento en términos de capacidad y fiabilidad. Sin embargo, la próxima generación de encaminamiento IP exigirá que las redes ópticas aporten tecnologías de enrutamiento y envío de paquetes a tasas de Terabit/s que sean totalmente compatibles con las técnicas de WDM (Wavelength Dense Multiplexing o Multiplexación por Longitud de Onda).

Las redes ópticas han pasado de ser redes basadas en conmutación de circuitos a redes basadas en la conmutación de paquetes ópticos aprovechándose de las ventajas que proporcionan los sistemas WDM como el mantenimiento de altas capacidades de transporte. Sin embargo, esta evolución no para y actualmente existe la posibilidad de encaminar paquetes de acuerdo a una etiqueta óptica evitándose así el procesamiento de los datos del paquete en el dominio electrónico: se llega a una solución prometedora que permite evitar cuellos de botella en los conmutadores. La conmutación totalmente óptica basada en etiquetas permite encaminar y enviar paquetes independientemente de su longitud de los paquetes y la velocidad de la red.

Hasta ahora las implementaciones de nodos ópticos que aparecen en la literatura realizan el procesamiento de los paquetes en el dominio electrónico usando diferentes tipos de modulaciones y multiplexaciones de subportadoras con una baja tasa de bit (destacar los estudios hechos en los Proyectos Europeos STOLAS (Switching Tehnologies for Optically Labeled Signals) o LABELS (Light wave Architectures for the processing of Broadband ELectronic Signals) que proponen arquitecturas híbridas de nodos optoelectrónicos. Sin embargo, con el propósito de alcanzar velocidades superiores a las conseguidas hasta ahora, transparencia en el formato de los paquetes y mayores eficiencias en la transmisión, todas las funcionalidades de un nodo de red, como la conmutación, enrutamiento y envío, han de ser implementadas en la capa física. Para ello, la capa óptica del nodo necesita implementar la correspondiente "inteligencia" para buscar en la tabla de enrutamiento y enviar los paquetes.

La conmutación totalmente óptica ha sido propuesta como un camino viable para resolver la diferencia de tasas de transmisión de la fibra óptica y de envío de los conmutadores que hasta ahora provocan grandes cuellos de botella en la redes como Internet. Esta técnica implementa el enrutamiento y envío de paquetes directamente en la capa óptica sin conversiones Optica/Electrónica/Óptica. La principal ventaja de esta alternativa es su habilidad de encaminar paquetes/ráfagas independientemente de la tasa de bit, formato y longitud de paquetes aumentando así la flexibilidad y granularidad de las redes. Además con esta implementación de nodo totalmente óptico se alcanzan altos anchos de banda al trabajar con etiquetas y se simplifica la implementación de los transmisores.

El presente Proyecto Fin de Carrera fue llevado a cabo en el contexto del proyecto Europeo LASAGNE (All-Optical LAbel Swapping employing optical logical Gates in NEtwork nodes) financiado por la Comisión Europea en su Sexto Programa Marco. El proyecto se enmarca en el escenario de una red óptica de conmutación de paquetes basados en técnicas de etiquetado óptico para paquetes ópticos de longitud fija.

El proyecto LASAGNE tiene como objetivo el diseño e implementación del primer nodo completamente óptico, modular y escalable capaz de operar a 40Gb/s. Dicho nodo lleva a cabo las operaciones de encaminamiento y envío así como conversión de longitudes de onda y conmutación de etiquetas enteramente en el dominio óptico. A pesar de su considerable mejora en el rendimiento respecto de otro tipo de nodos con conmutación de paquetes ópticos, hay algunas cuestiones que han de ser analizadas con el fin de realizar futuros nodos de conmutación de paquetes totalmente ópticos lo suficientemente eficientes.

Por ello en el presente proyecto se analizan algunos problemas típicos en los nodos como por ejemplo la contienda de paquetes. Los nodos completamente ópticos pueden beneficiarse de versátiles estrategias de almacenamiento en buffers ópticos para evitar la contienda. Numerosos grupos de investigación han presentado diferentes estrategias de buffering para resolver este problema en nodos de conmutación de paquetes ópticos. Sin embargo, no hay estudios equiparables para el caso de nodos totalmente ópticos. Es por ello que en el presente proyecto diferentes alternativas de implementación de buffers han sido propuestas con el fin de resolver de forma efectiva la contienda.

Por otro lado, las más modernas aplicaciones y servicios de Internet exigen mayores y más versátiles funcionalidades en las redes de transportes, como por ejemplo la distribución de vídeo bajo de demanda o teleconferencia. Es por ello que los futuros nodos ópticos deben implementar funciones que permitan el multicasting. En este proyecto se proponen y demuestran varios métodos para llevar a cabo el multicast en el dominio óptico, todo un reto dada la inexistencia de una memoria óptica.

Como se ha venido diciendo hasta ahora el presente proyecto se centra en el análisis de un nodo de conmutación de paquetes completamente óptico así como en la propuesta de nuevas estrategias que permitan mejorar su rendimiento y la proposición de nuevas arquitecturas para soportar el tráfico multicast. El estudio de este nodo se lleva a cabo utilizando un simulador realizado para emular el comportamiento de tal nodo. Por lo tanto se consiguen contribuciones en dos campos:

- Resolución del problema de contienda por medio de distintas configuraciones de buffers para los nodos de conmutación de paquetes totalmente ópticos.

- Diseño y evaluación de arquitecturas Multicast para dicho nodo.

Particularmente, los objetivos de proyecto son:

- Presentación de un concepto técnicamente viable para nodo con conmutación de paquetes totalmente óptico orientado al mundo comercial.
- Presentación del simulador desarrollado y utilizado para implementar las técnicas propuestas en el proyecto.
- Evaluación del rendimiento de tráfico de un nodo de conmutación de paquetes totalmente óptico para diferentes configuraciones de resolución de contienda basadas en buffers.
- Proposición de evaluación de nuevas arquitecturas de conmutación de paquetes para un nodo totalmente óptico que resuelva el tráfico multicast.

ORIGINALIDAD

Este proyecto se inicia con los resultados obtenidos en el Proyecto Europeo LASAGNE en el que el nodo es un punto de la red donde la información se concentra y se procesa para, posteriormente, encaminarla a otras partes de la red o a los usuarios. Hasta el momento, este proceso de la información en la Red se hace convirtiendo los datos que viajan por la fibra óptica en señales electrónicas, para después volverlas a trasformar en señales ópticas, lo que limita la velocidad del proceso.

El proyecto Lasagne intenta crear la tecnología necesaria para que todas las funciones de este procesamiento de la información en internet puedan hacerse de forma completamente óptica, sin convertir los datos en señales electrónicas, como ocurre actualmente. La ventaja que aportará una red internet completamente óptica es una mayor velocidad en los procesos, tanto para encaminar la información desde los nodos a su destino final, como para insertarla y extraerla de la red.

El tratamiento de la información que viaja por internet completamente óptica no se ha realizado hasta el momento en Europa y con este proyecto se pretende ponerse a la altura de las investigaciones que se están llevando a cabo en Estados Unidos y en Japón.

Para poder tratar la información directamente sobre la luz (procesamiento óptico de la información) hace falta desarrollar la réplica óptica de la tecnología actual electrónica existente en la red. El proyecto Lasagne creará la tecnología necesaria para conseguir una internet completamente óptica, sin transformaciones electrónicas. Para abordar esta transformación tecnológica se desarrollarán las "puertas lógicas completamente ópticas" que son las operaciones más simples que, agrupándolas, permiten realizar cualquier operación compleja que servirá para comparar datos y tomar decisiones para redistribuir la información en la red sin que sea necesaria la conversión electrónica.

Este presente proyecto va un paso más allá de los estudios realizados en el proyecto LASAGNE e introduce mejoras al nodo totalmente óptico así como nuevas funcionalidades que le permitan adaptarse a las exigencias de las aplicaciones actuales en Internet. Para ello se ha desarrollado un simulador llamado AOLSim con el que se pretende obtener las gráficas que demuestren las mejoras en el rendimiento del nuevo nodo totalmente óptico antes distintos tipos de tráfico. Este programa está escrito sobre Linux y como tal es de libre distribución para el uso y disfrute de cualquier usuario.

Comenzamos analizando el problema de contienda de paquetes en los nodos de una red. Los nodos completamente ópticos pueden beneficiarse de versátiles estrategias de almacenamiento en buffers ópticos para evitar la contienda. Numerosos grupos de investigación han presentado diferentes estrategias de buffering para resolver este problema en nodos de conmutación de paquetes ópticos. Sin embargo, no hay estudios equiparables para el caso de nodos totalmente ópticos. Es por ello que en el presente proyecto diferentes alternativas de implementación de buffers han sido propuestas con el fin de resolver de forma efectiva la contienda para el caso concreto de nodos totalmente ópticos acercándonos cada vez más a una situación que muchos usuarios desearían para no experimentar los retardos que pueda presentar actualmente Internet.

En este proyecto se proponen y demuestran varios métodos para llevar a cabo el multicast en el dominio óptico, todo un reto dada la inexistencia de una memoria óptica. De esta manera conseguimos adaptarnos a las más modernas aplicaciones y servicios de Internet que exigen mayores y más versátiles funcionalidades en las redes de transportes, como por ejemplo la distribución de vídeo bajo de demanda o teleconferencia.

Vemos pues que las ambas líneas tratadas en el proyecto son completamente innovadoras y están recogidas en tres artículos a los que me remito en los anexos.

RESULTADOS

El presente proyecto se centra en el análisis de un nodo de conmutación de paquetes completamente óptico así como en la propuesta de nuevas estrategias que permitan mejorar su rendimiento y la proposición de nuevas arquitecturas para soportar el tráfico multicast. El estudio de este nodo se lleva a cabo utilizando un simulador realizado para emular el comportamiento de tal nodo. Por lo tanto se consiguen contribuciones en dos campos:

- Resolución del problema de contienda por medio de distintas configuraciones de buffers para los nodos de conmutación de paquetes totalmente ópticos.

- Diseño y evaluación de arquitecturas Multicast para dicho nodo.

Ambas líneas de investigación junto con los resultados obtenidos han sido publicadas en artículos para Congresos Internacionales a los que les remito para analizar las gráficas que verifican los resultados que en este apartado paso a describir:

- Las propuestas de configuraciones basadas en buffering para evitar los problemas de contienda en nodos de conmutación completamente ópticos son:

    - Buffers en la salida, con un número variable de líneas de retardo o un número variable de bucles por línea de retardo.
    - Buffers en la entrada.

  En el primer caso el rendimiento del nodo totalmente óptico se ve condicionado por el modelo de tráfico utilizado en las simulaciones. Por ejemplo, a pesar de la mejora en dos órdenes de magnitud de la tasa de pérdida de paquetes para el tráfico de Bernouilli, la efectividad de la configuración basada en buffers a la salida del nodo es bastante limitada cuando consideramos tráfico auto-similar (también denominado fractal), que se aproxima en mejor grado al tráfico soportado en Internet. En este proyecto se consigue presentar una configuración de conmutador de paquetes totalmente óptico que elimina completamente el problema de contienda y cuyo funcionamiento se expone en el presente proyecto así como en el artículo “Buffering Strategies for Contention Resolution in All-Optical Label Swapping Switches” publicado en el congreso NOC, Conference on Optical Networks celebrado en Berlín en Mayo de 2007 del que soy autora.

- La otra línea de investigación del presente proyecto es la introducción de capacidades multicast en el nodo de conmutación de paquetes totalmente óptico. Se proponen dos nuevas arquitecturas multicast para dicho nodo:

    - Configuración con recirculación de paquetes multicast.
    - Configuración con envío inmediato de los paquetes multicast.

Se realizaron múltiples simulaciones con distintos casos de tráfico de paquetes, y se observó como la arquitectura de envío inmediato es claramente más eficiente a la alternativa con recirculación de paquetes. Además, comprobamos que esta arquitectura llega a alcanzar rendimientos similares a la arquitectura que sólo admite tráfico unicast. Los resultados obtenidos fueron objeto de publicación en los artículos “Cost Reduction and Traffic Performance Improvement using Direct Forward Optical Layer Multicast in Optical Label Switching Nodes“ y “Traffic performance evaluation of optical label switching nodes with optical layer multicast“ publicados en las conferencias ECOC (European Conference on Optical Communications) y APOC (Asian Presentation on Optical Communications) respectivamente.

Este proyecto ha sentado las bases para futuros proyectos que se están llevando a cabo en las Universidades de Eindhoven, en Holanda, y de Copenhage, en Dinamarca. Actualmente se sigue investigando sobre la capacidad multicast de los nodos de conmutación de paquetes totalmente ópticos con el fín de ser integrados en redes conocidas como la NSFNET.

APLICABILIDAD

Para comenzar el análisis de las aplicaciones que tienen los contenidos expuestos en el presente proyecto veamos un ejemplo para mostrar la revolución que han supuesto las nuevas tecnologías de fibra óptica en las comunicaciones modernas:

Son las 11:30 de la noche, se encuentra en Barcelona en viaje de negocios y desea consultar los mensajes de su oficina de Madrid. En primer lugar, llama y consulta los mensajes de voz. A continuación, conecta su ordenador portátil en el enchufe de teléfono de la habitación del hotel, pulsa algunas teclas y recibe los mensajes de correo electrónico de un cliente potencial de Valencia, de su madre en el pueblo y de un socio comercial de Inglaterra. Antes de responderles, realiza una investigación rápida en Internet, buscando el nombre del grupo de noticias en línea que le mencionó al socio comercial y el título de un libro que desea recomendar a su madre. Unas cuantas pulsaciones de teclas más y en unos instantes sus cartas electrónicas llegan a Valencia y a Inglaterra. Entonces, como sabe que su madre se enfadará si no le hace una llamada para comentarle el libro que le aconseja coge su teléfono y se dispone a efectuar tal llamada.

Hace tan sólo 10 años, estas comunicaciones casi instantáneas que reducen el tamaño del mundo no hubiesen sido posibles; los componentes tecnológicos esenciales de la informática y de las comunicaciones acababan de aparecer. Posteriormente, en 1988, se instaló el primer cable de fibra óptica transatlántico, y la "superautopista de la información" estaba en camino de hacerse realidad.

Las fibras ópticas constituyen el eje central del sistema de telecomunicaciones global. Estos extraordinarios filamentos de cristal, cuyo grosor es inferior al de un pelo humano, pero cuya resistencia es superior a la del acero, fueron diseñados para transportar las grandes cantidades de datos que se pueden transmitir a través de una forma de luz relativamente nueva: los rayos láser muy concentrados. Tanto los láseres como las fibras ópticas han aumentado considerablemente la capacidad de la red telefónica internacional. Junto con las increíbles mejoras conseguidas también en el campo de la informática, la nueva tecnología de comunicaciones ha favorecido el crecimiento exponencial del fenómeno conocido como Internet.

La fibra óptica facilita el medio que llega a transmitir tasas a nivel de Terabit/s que hacen posibles las comunicaciones ultra-rápidas. Sin embargo, los conmutadores modernos no son capaces de hacer frente a tales tasas dada su obligatoriedad de procesamiento en el dominio electrónico, lo que exige conversiones del dominio óptico al electrónico y posteriormente de nuevo al óptico, lo que ralentiza el envío de paquetes dificultando así el desarrollo y evolución de Internet.

En este proyecto se propone un conmutador que evite el paso al dominio electrónico y que sea capaz de efectuar todo el procesamiento necesario para el encaminamiento y reenvío en el dominio óptico. La construcción de la parte de este nodo consistente en la búsqueda de la ruta que ha de seguir un paquete ya es factible gracias a construcciones del módulo AOLS (All-Optical Label Swapping) llevadas a cabo en el centro de nanotecnología de la Universidad de Valencia. En este proyecto se han llevado a cabo simulaciones del nodo entero obteniendo excelentes resultados de rendimiento y tiempo de envío.

Finalmente, dado el crecimiento de las aplicaciones en Internet que requieren el procesamiento de tráfico multicast, como por ejemplo la vídeo-conferencia, vídeo bajo demanda, juegos on-line, etc, se proponen arquitecturas de un nodo totalmente óptico capaces de afrontar los nuevos retos que nos depara la red de redes, Internet.

ANEXOS

Buffering Strategies for Contention Resolution in All-Optical Label Swapping Switches

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Abstract

All-optical label swapping (AOLS) is an effective solution to realize ultra-fast, high capacity all-optical switching for future packet-based optical networks. It implements packet routing and forwarding directly in the optical layer without Optical-Electronic-Optical (OEO) conversion. One of the most critical issues in designing efficient AOLS packet switches is *where* and *how* to place optical buffers to solve packet contention, which directly influence the performance and scalability of AOLS packet switches.

A number of research groups have reported various buffering strategies for contention resolution in Optical Packet Switches (OPS). Among those, a single stage of delay lines connected in either a forward or feedback configuration, as the ones used in KEOPS or SMOP projects, is mostly implemented because its excellent improvement in switch performance in terms of packet loss rate without extremely complex switch architectures. However, for all-optical switching node architectures such as AOLS switches investigated and demonstrated in the European IST-LASAGNE project, only single packet slot buffering has been considered so far, which did not prove to have significant improvement on the node traffic performance. Therefore, more complicated buffering strategies need to be developed to solve the AOLS node contention effectively.

In this paper, two queuing models for output-buffered AOLS packet switches are proposed and assessed through traffic simulations with two different types of traffic models: Bernoulli and Self-similar. We compare the performance of these two models in terms of Packet Loss Rate and Network Throughput. Afterwards, we proceed to evaluate an input-buffered AOLS packet switch using the same traffic models. The input-buffered architecture can efficiently avoid packet loss by employing more internal and external wavelengths comparing to the output-buffered scheme under the same traffic load.

Cost Reduction and Traffic Performance Improvement using Direct Forward Optical Layer Multicast in Optical Label Switching Nodes

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Abstract *We propose a simpler, faster, more efficient and economical multicast concept for passive waveguide-based optical label switching nodes. We analyze its advantages in terms of cost and traffic performance in comparison with the recirculation approach.*

Introduction

Future telecommunications networks are expected to support the steeply increasing multicast traffic from multimedia or enterprise applications such as high-definition TV, online games, video-on-demand, video conference and optical storage area networks. In order to deliver large amount of data more efficiently, more and more networking functions are being moved to the optical layer. All-optical solutions on switching, routing and multicasting are of crucial importance for realizing a truly intelligent, transparent and broadband optical infrastructure.

Optical layer multicast methods reported so far are based on three approaches: broadcast-and-select [1], light-splitting [2] and recirculation schemes in optical nodes [3-5]. The first two structures suffer from excessive optical losses due to the power splitting. The last one, recirculation or feedback configuration, has been the most exploited method for multicast in optical label switching (OLS) nodes.

In this paper, we propose a simpler, faster, more efficient and economical multicast concept for passive waveguide-based OLS nodes. Moreover, we analyze its benefits in terms of cost and traffic performance in comparison with the recirculation approach.

All-Optical Label Switching Node with Multicast

Fig. 1 presents the basic 2x2 schematic OLS node architecture based on our multicast concept. To demonstrate its advantages over the recirculation multicast approach, we adopt the same node dimension and configuration as in [5], except that the recirculation loops in [5] are not necessary anymore, because the multicast functionality is directly implemented at each all-optical label swapper (AOLSW) in Fig. 1.

The node has two *input* and *output* fibers, each carrying four wavelengths. It also has a set of *add-drop* ports for the local traffic. The AOLSW performs label processing by comparing the packet label with the forwarding index, and converts the packet onto appropriate wavelength(s) specified by the all-optical flip-flops (AOFFs), which are set by the label processors [5,6], as shown in Fig. 2. The array waveguide gratings (AWGs) realize direct optical layer uni- or multicast based on the packet wavelength(s).

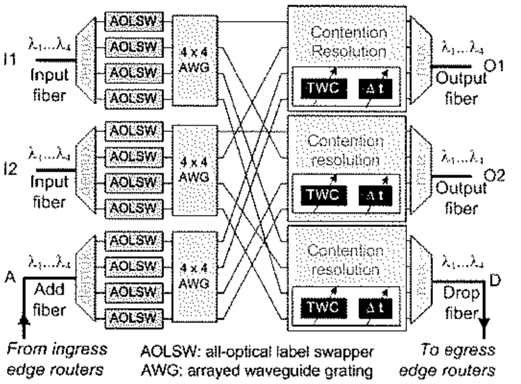

Fig. 1 Schematic 2x2 OLS node architecture

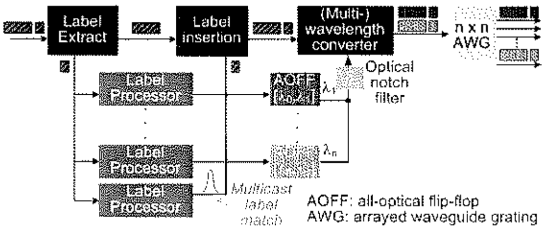

Fig. 2 AOLSW block diagram and logic functions

The AOLSW can employ all the functioning subsystems as in [5] with one fundamental design difference: the wavelength converter can have multiple continuous wave (CW) inputs and perform multi-wavelength conversion (MWC) [7,8]. This is achieved by activating multiple AOFFs when a multicast label is matched. Note that the multicast labels do not have to be special labels different in nature from the unicast ones. For an *NxN* node, there are 2^N possible different ways of forwarding an incoming packet: *N* of them are for unicast to each output fiber port, and the rest for multi- or broadcast. With the recirculation multicast approach, all the packets with 2^N-N different multicast labels are sent to the recirculation loops in order to be further processed, while with direct AOLSW multicast these are already taken into account at the first label processing stage. Multicast is then executed at the AOLSW level instead of the OLS node level.

So far, one-to-eight MWC has been reported [8], proving good feasibility for current OLS node multicast applications. A working model of the AOLSW has also been demonstrated for unicast [6].

Cost Reduction by Physical Resource Savings

The AOLSW multicast approach brings various benefits including physical component savings. Table 1 presents the numerical calculation of the *minimum* resource requirements of the recirculation and direct forward multicast approaches for an *N*x*N* node in a network of *W* wavelengths.

Table 1 Minimum resource requirement per node for the two multicast schemes

	Recirculation	Direct Forward	*Saved Resource*
AOFF	*$(W+4)N^2+2WN$*	*$(W+1)N^2+WN$*	**$3N^2+WN$**
AWG ports	*N^2+4N*	*N^2+2N*	**$2N$**
AOLSW	*$(W+2)N$*	*$(W+1)N$*	**N**
Loops	*N*	*0*	**N**

From the table we can observe that with the direct forward multicast scheme, considerable physical components can be spared. On the OLS node level, the resource reduction is proportional to the node dimension *N* for the number of AWG ports, AOLSW and recirculation loops required. On the AOLSW level, the resource reduction is quadratic to the node dimension *N* when the number of the network wavelengths *W* is fixed, and proportional to the network wavelengths *W* when the node dimension *N* is fixed.

Traffic Performance Evaluation

To demonstrate the traffic performance improvement of the direct forward (`Multicast2`) scheme over the recirculation (`Multicast1`) scheme, self-similar traffic driven simulations of the node in Fig. 1 were carried out under the same node dimension and configuration in [5]. Both nodes are for fixed length packets. We used an average IP packet size of 512 bytes, but this parameter does not matter for the packet loss rate and network throughput calculations. At each time slot, maximum ten synchronized packets are generated and sent to the node. Among those, the possibility of generating a multicast packet per input fiber port is on average *one* in every *three* packets. Whenever a multicast label is detected, the packet will be forwarded to both output fiber ports.

Three contention resolution (CR) conditions were investigated for these two multicast schemes:

- `NoCR`: No CR implemented. In case of contention, the packet(s) will be dropped.
- `WC`: Only wavelength conversion is implemented.
- `WCFB`: In case of contention, the node will first look for an available output wavelength. If this is not possible, the node can buffer the packet for one packet duration.

Fig. 3 shows the simulation results. We can see that the direct forward scheme performs always considerably better than the recirculation scheme under the same CR conditions. Moreover, the performance of `Multicast2` without any CR strategy is very close to that of `Multicast1` with `WC` and `WCFB`. When `WC` is introduced to `Multicast2`, significant improvement is achieved. Further introducing one-slot optical buffering to `Multicast2` shows additional performance enhancement, which is much more noticeable than that with `Multicast1`.

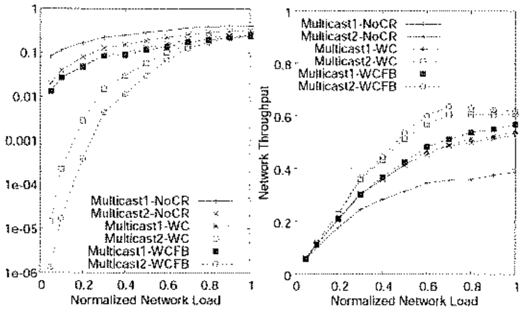

Fig. 3 Traffic performance simulation results of the two multicast schemes using different contention resolution (`Multicast1`: recirculation; `Multicast2`: direct forward)

The large packet loss ratio obtained for the recirculation scheme in [5] is due to the fact that it can process only *one* multicast packet per time slot, unless more recirculation loops are added [4], which leads to further increase in the other required resource in Table 1 such as the number of AOFFs, AWG dimensions and AOLSWs, as well as internal wavelength resource. In order to keep the node size, complexity and cost reasonable, so far only limited multicast function could be realized for a basic 2x2 node [4]. While with the direct forward scheme, we can process as many multicast packets as needed in every time slot, as the multicast function is integrated inside each AOLSW.

Conclusions

We propose a novel multicast scheme for passive waveguide based optical label switching node. Numerical analysis shows that this scheme requires considerably less physical components resource than the conventional recirculation multicast approach. Traffic performance simulation proves the performance improvement to be also significant.

Acknowledgement

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Traffic performance evaluation of optical label switching nodes with optical layer multicast

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ABSTRACT

All-optical label switching (AOLS) is a promising approach of implementing label switching for packet routing and forwarding in the optical layer at high speeds close to fiber line-rates. In this paper, AOLS node architectures with unicast and two multicast approaches are presented. The multicast approaches are referred to as feedback and feed-forward multicast, respectively. We compare these node architectures and evaluate their traffic performance in both unicast and multicast cases with different contention resolution schemes. Simulation results on AOLS nodes of the same dimension are analyzed in terms of packet loss ratio and network throughput.

Keywords: All-optical, label switching, Bernoulli, contention resolution, multicast, packet loss ratio, recirculation, self-similar, traffic performance

1. INTRODUCTION

The rapid growth of Internet and multimedia data traffic poses a potential challenge for the telecom transport networks. The enormous increase of data traffic demands the future backbone transport networks to be able to deliver multiplexed high bit-rate data packets with high efficiency. The huge capacity of optical fiber and the development of the wavelength division multiplexing (WDM) technologies have greatly increased the transmission link capacity. However, currently optical transport networks still deploy optical circuit switching or Point-to-Point wavelength channels. It is generally believed that optical packet switching (OPS) with appropriate granularity will significantly improve the optical network throughput, efficiency and bandwidth utilization.[1]

In recent years, label switching technologies such as multi-protocol label switching (MPLS) and asynchronous transfer mode (ATM), as well as various label coding techniques have considerably boosted the packet handling speed of the transport nodes. Packet switching and forwarding based on swapping short local labels instead of locating the global unique Internet protocol (IP) addresses has dramatically enhanced the throughput of the network nodes. Nevertheless, these techniques and protocols have been only employed in routers that deal with data packets in the electronic or electro-optic domain.

To support packet switching and forwarding at fiber line-rates up to Tb/s, node technologies that can realize packet handling in the optical layer are required. Electronic packet header processing will no longer meet the demands. All-optical label switching (AOLS) is a new concept of implementing this label swapping technique for packet switching in the optical domain.[2] AOLS technologies combined with OPS could be a solution for the next generation optical data networks. However, most of the AOLS or optical label switching (OLS) nodes investigated so far provide only limited multicast functionalities employing broadcast-and-select schemes[3] or feedback configurations.[4–6] The former results in a large amount of unwanted network traffic, creating network congestions, and suffer from excessive optical losses due to the passive optical power splitting via the distributors.[3]

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The latter, also sometimes referred to as the recirculation multicast approach, has been the most exploited multicast method for AOLS and OLS nodes studied and demonstrated in the last 5~10 years. The main disadvantage of such multicast configurations is that it can support only limited multicast traffic depending on the number of feedback loops and multicast capable ports installed.[4–6] Moreover, by implementing feedback structures, multicast traffic experiences longer delay, encounters more optical losses and goes through more active components, which also reduce the packet handling efficiency and optical node transparency.

Previously, no study has been done on the traffic performance of AOLS unicast and different multicast configurations under various data traffic patterns. Recently, we proposed and evaluated a new multicast approach: feed-forward multicast.[7] It eliminates the feedback structure by supporting multicast functionality directly in the optical layer inside the label switching unit before the arrayed waveguide grating (AWG). We have analyzed its performance based on a basic 2×2 structure deploying self-similar traffic model comparing to the conventional feedback multicast switch of the same node dimension. Our simulation results showed that this multicast concept is simpler, faster, more efficient and economical for passive waveguide-based OLS nodes with significant performance improvement.[7]

In this paper, we assess and compare the performance of OLS unicast and the two multicast architectures of different node dimensions under the Bernoulli and self-similar traffic conditions. Moreover, we investigate the impact of various contention resolution (CR) schemes on the packet loss ratio (PLR) and network throughput (NT) of the switching nodes.

2. OPTICAL LABEL SWITCHING NODES WITH UNI- AND MULTICAST

The evaluated unicast and feedback multicast OLS node architectures were based on the AOLS node architecture and functioning blocks studied, validated and demonstrated in the European Commission funded FP6 project IST-LASAGNE (all-optical label swapping employing optical logic gates in network nodes).[6,8]

The LASAGNE AOLS nodes include the following functional stages: input fiber ports, wavelength demultiplexers (demux's), all-optical label swappers (AOLSWs), AWG routers, CR blocks, wavelength multiplexers (mux's), and output fiber ports. The main operating principle of the LASAGNE switch is to use all-optical eXclusive OR (XOR) correlators to match the incoming label with the keyword indexes of the node forwarding table, wavelength convert the whole label-swapped optical packet, and then route the new packet to the right output port according to its wavelength by an AWG. Such a switching procedure and label swapping node structure have already been previously employed and demonstrated by the The European Commission funded FP5 project IST-STOLAS (switching technologies for optically labeled signals),[4] expect that in the STOLAS project electronic label processing was adopted.

2.1 AOLS Unicast

Figure 1 presents the schematic diagram of a basic 2×2 AOLS unicast node for four-channel WDM AOLS networks, including an *Add* fiber port for connecting to an ingress edge router and a *Drop* fiber port to an egress edge router for local traffic.

The node processes optical packets in the following procedure: at the input line ports, the WDM channels are demultiplexed into packets of single wavelengths. From each output of the demux an optical packet enters an AOLSW. Inside the AOLSW, the packet label is extracted and compared to a list of keywords, which are generated locally according to the forwarding table, and serve as its looking-up indexes. Each keyword maps a corresponding entry, where a new label pattern and an internal packet wavelength are specified. The relevant new label is inserted in front of the payload, and the whole packet is converted into the internal wavelength. Following the AOLSW, the AWG routes the new packet to the desired output(s) of the switch. Tunable wavelength converters (TWCs) near the outputs are employed to convert the optical packets from internal wavelengths for the AWG routing onto acceptable vacant external wavelengths, to avoid contention at the output line ports.

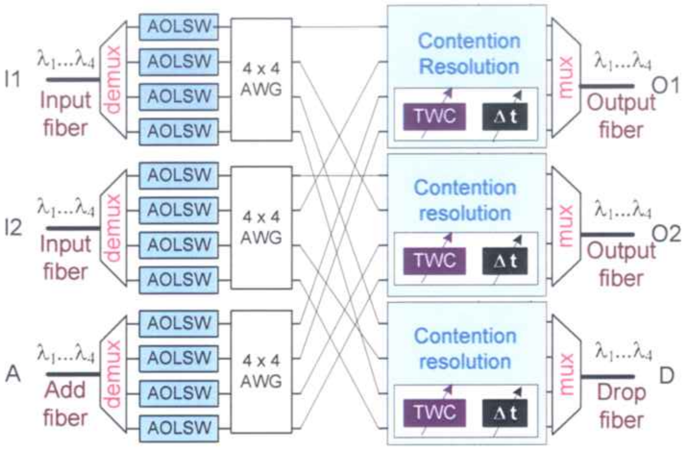

Figure 1: 2×2 AOLS unicast and feed-forward multicast node architecture

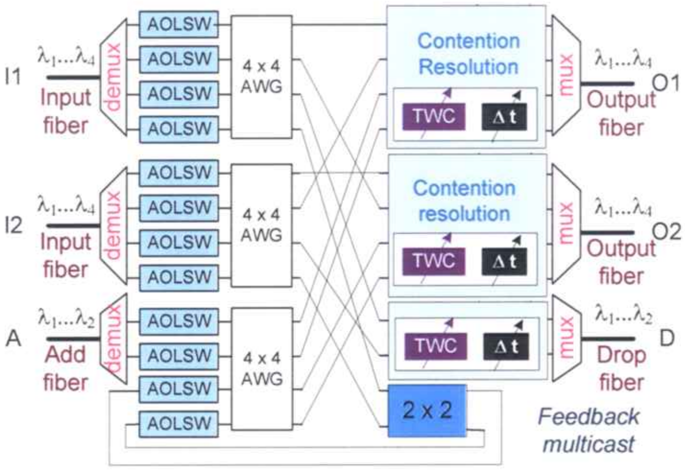

Figure 2: 2×2 AOLS feedback multicast node architecture

2.2 AOLS Feedback Multicast

AOLS feedback multicast in a 2×2 node is implemented by recirculating the multicast packet to a feedback configuration, duplicating the packet, and processing the duplicated multicast packets again at the input side of the switch in order to forward them to both output fiber ports,[6] as illustrated in Fig. 2. Multicast by means of feedback configurations must be executed at the OLS node level. Moreover, part of the node resources need to be dedicated to the recirculation and the re-processing of the multicast packets, therefore, the percentage of the resources that is used for forwarding the packets to the next nodes is lower. Hence, the NT of such multicast switch is lower, and the efficiency of such nodes is depleted.

Another drawback of the multicast node architecture shown in Fig. 2 is that this switch can only process *one* multicast packet from both input fiber ports at a time, as the feedback construction can only accommodate *one* multicast connection. This way, the switching is envisaged to be able to keep the packet loss ratio low only when the number of multicast packets represents a relatively small fraction of the total number of generated packets. if the multicast traffic constantly occupies a large portion of the total traffic, additional multicast ports or converting existing unicast ports to multicast ports are required to be able to handle the extra amount of multicast traffic, and a relevant number of optical feedback circuits also need to be introduced. This also means that the packet forwarding efficiency and the NT of the node is further reduced.

2.3 AOLS Feed-Forward Multicast

AOLS feed-forward multicast is executed at each AOLSW level by all-optical multi-wavelength conversion,[9–11] which is achieved by driving the wavelength converter in the AOLSW with multiple continuous waves on the desired wavelengths when a multicast label is matched.[7] The architecture of a 2×2 AOLS feed-forward multicast node is the same as a 2×2 AOLS unicast node, as presented in Fig. 1. The difference between an AOLS feed-forward multicast node and an AOLS unicast node is distinguished by the way each AOLSW handles an optical packet. In the cases of unicast and feedback multicast, the AOLSW can only convert the packet onto one single wavelength.[6,8] Consequently, the optical packet is routed only *one* output port of the AWG, and hence either *one* of the output fiber ports or the feedback circuit; while in the case of feed-forward multicast, the AOLSW is able to convert the packet onto multiple appropriate wavelengths specified by the control block, which is set by the label processors.[7] The same optical data information on different wavelengths is then simultaneously forwarded to different output ports of the AWG that are connected to different output fiber ports.

3. TRAFFIC PERFORMANCE EVALUATION

To evaluate and compare the traffic performance of the above node architectures under different CR schemes, simulations deploying Bernoulli and self-similar traffic models were carried out. Bernoulli is the simplest traffic pattern for OPS. The probability that a packet appears in a concrete slot of time is $\rho \in (0,1)$, i.e. follows a Bernoulli distribution. Self-similar traffic proves to represent realistic network traffic characteristics, such as Internet traffic.[12–14] Therefore, generating synthetic self-similar traffic is important to achieve credible simulation results.

3.1 Simulation Parameters and Conditions

3.1.1 Measured performance parameters

LASAGNE AOLS nodes were designed for fixed-length optical packets. In all our simulations, we deployed an average IP packet size of 512 bytes. However, the exact value of this parameter is not important for the PLR and NT calculations, which are the two parameters that are mostly used in assessing network traffic performance in an optical packet-based environment. They indicate network reliability and utilization.[15]

PLR is defined as the total number of dropped packets divided by the total number of packets generated:

$$PLR = \frac{packet_{dropped}}{packet_{generated}}. \tag{1}$$

NT is the fraction of the network resource, in this case a single node, that successfully delivers packets.[15] The simulated NT is calculated as:

$$NT = \frac{packet_{delivered}}{packet_{generated} + null_{generated}}, \tag{2}$$

where $null_{generated}$ is the number of null packets, i.e. void time slots when there are not packets generated.

For multicast traffic simulations, the above $packet_{generated}$ in Eqs. (1) and (2) become

$$packet_{generated} = packet_{generated} + packet_{duplicated} = 2 \times packet_{generated}. \tag{3}$$

3.1.2 Assessed contention resolution schemes

Three CR schemes were applied to each node architecture, which are:

- `NoCR`: No CR implemented. In case of contention, the packet(s) will be dropped.
- `WC`: Only wavelength conversion is implemented.
- `WCFB`: Wavelength conversion with further one-slot packet buffer is implemented.

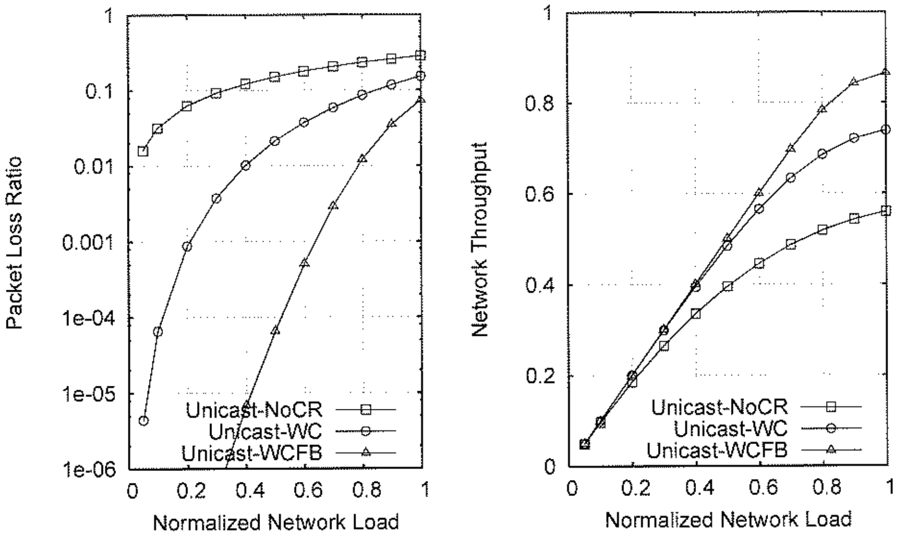

Figure 3: Simulation results of unicast node with Bernoulli traffic

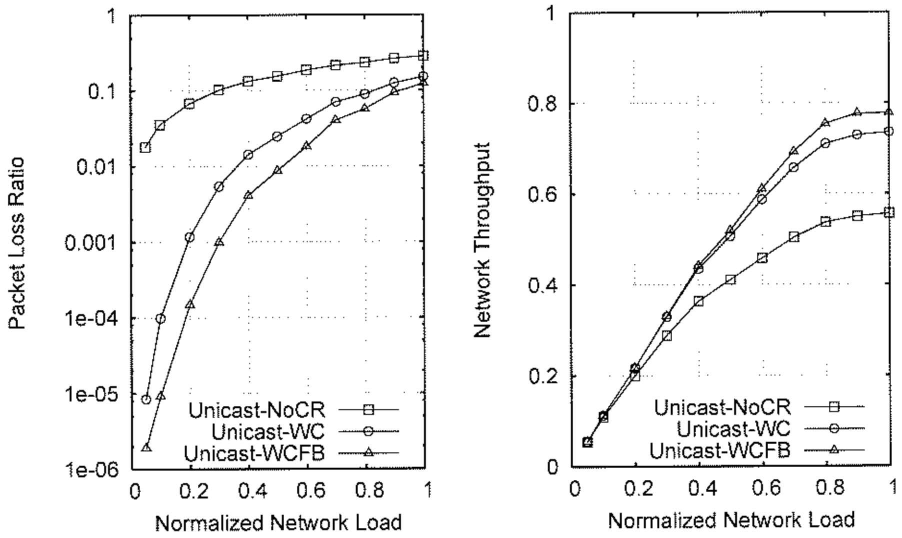

Figure 4: Simulation results of unicast node with self-similar traffic

3.2 Simulation Results

3.2.1 Unicast performance

In unicast simulations of the architecture illustrated in Fig. 1, at each time slot, maximum *twelve* synchronized packets are generated and sent to the node. Figure 3 and 4 present the PLR and NT performance of the unicast node under Bernoulli and self-similar traffic conditions, respectively. We can observe that by introducing one-slot buffer into the CR scheme, with self-similar traffic model it is less efficient than with Bernoulli traffic. This is because of the difference between the traffic model characteristics. Self-similar traffic sends a burst of packets during a *ON* period, during which the one-slot buffer is likely to be constantly occupied so that when more packets come in they can only be dropped. Therefore the PLR starts to increase quickly and the NT does not experience much improvement. While in a *OFF* period the buffering resource is not utilized efficiently. On the other hand, Bernoulli traffic has a homogeneity nature, which spread packets over all the simulation time slots

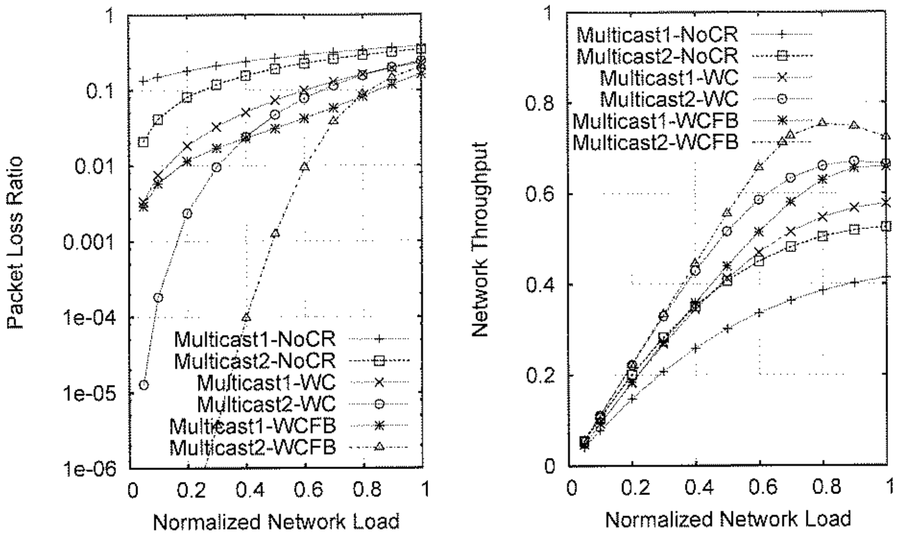

Figure 5: Simulation results of multicast node with Bernoulli traffic

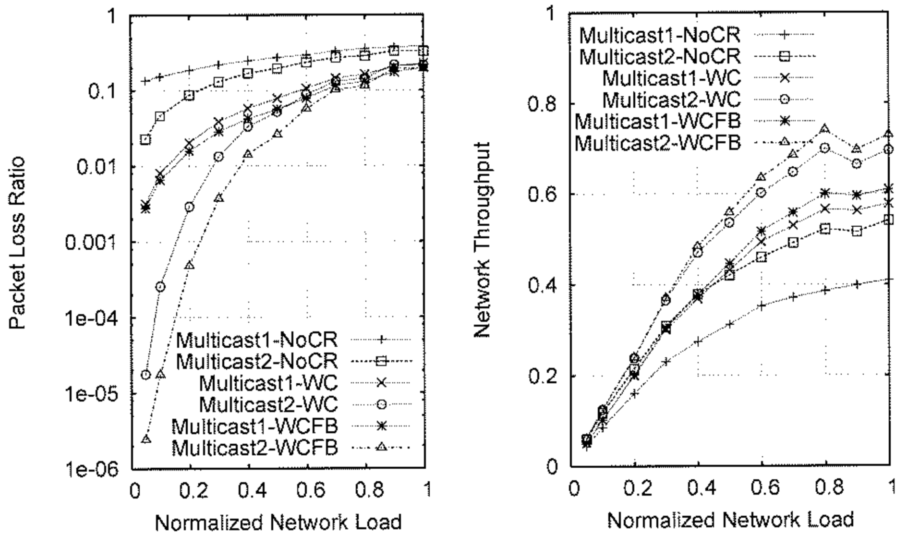

Figure 6: Simulation results of multicast node with self-similar traffic

for a certain load to avoid packet bursts. Consequently, the packets that are stored in the buffer can be forward quickly and the slot is available again for upcoming contended packets.

3.2.2 Multicast performance

One multicast port

Multicast performance of the feedback and feed-forward architectures, shown in Fig. 1 and Fig. 2, are assessed. At each time slot, maximum *twelve* synchronized packets for Fig. 1 and *ten* for Fig. 2 are generated and sent to the nodes. In this set of simulations, we only configured the first input fiber port of each node with multicast traffic, while the second input fiber port receives only unicast traffic. The possibility of generating a multicast packet for the first port was set on average *one* in every *three* packets. Whenever a multicast label is detected, the packet is forwarded to both output fiber ports. The two node architectures employ the same node dimension

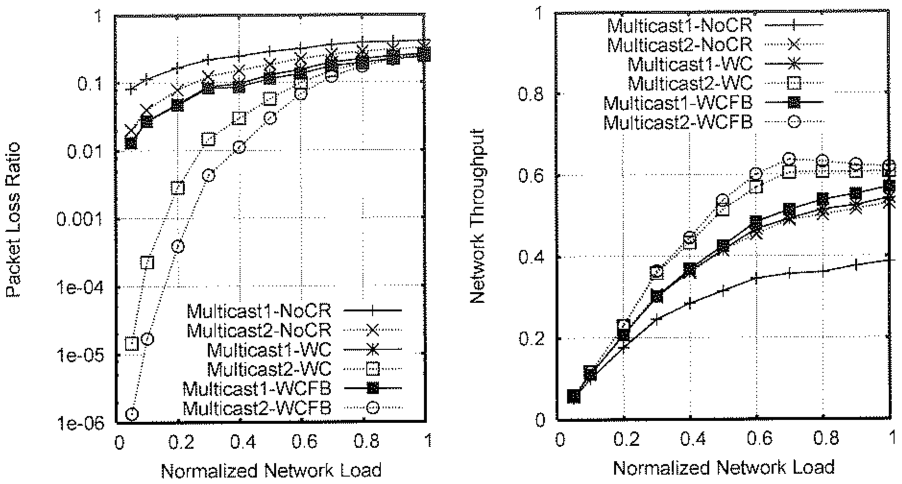

Figure 7: Simulation results of multicast node with self-similar traffic with the same intended throughput

and active components, and are referred to as `Multicast1` and `Multicast2` in the simulation results plotted together in Fig. 5 and Fig. 6.

Comparing the traffic performance of the multicast architectures with Bernoulli traffic and self-similar traffic, we perceived again that when fiber buffering is introduced, both multicast nodes perform better with the Bernoulli traffic pattern than with the self-similar one. The reason is the same as that in the unicast case, which is determined by the traffic model characteristics.

From the Bernoulli traffic driven results in Fig. 5, we also observed that as the network load becomes higher, the network reliability of the `Multicast1-WCFB`, indicated by the PLR curves, started to excel both `Multicast2-WC` and `Multicast2-WCFB`. This is because at a high network load, the feedback configuration also serves as a buffer for the congested situation. Therefore, `Multicast1` physically have more packet buffers than `Multicast2`, which tries to forward the packets straight to the output fiber ports. As Bernoulli traffic model distributes the traffic load evenly across all the simulation time slots, the packets that are in the buffer and feedback circuit can seek the next available time slots to be forwarded to the output fiber ports instead of being dropped. As a result, `Multicast1-WCFB` also has a better NT performance. In the case of self-similar traffic, the feedback circuit do not improve much the `Multicast1` performance when functioning as a buffer due to the bursty nature of the traffic. The explanation is similar as in the unicast case in Sec. 3.2.1.

The self-similar traffic driven results presented in Fig. 6 prove that under bursty traffic conditions, the feed-forward multicast scheme performs always considerably better under the same CR conditions. With both multicast architectures, introducing `WC` is always more efficient in solving the contention than introducing `FB`, which demonstrated to have only minor improvement in the node performance. Feed-forward multicast scheme with only `WC` CR scheme already achieve significantly better results than feedback multicast scheme with `WCFB`.

Two multicast ports

In this set of simulations, both input fiber ports can receive multicast traffic. The probability of generating a multicast packet is the same as previous, that is, on average *one* multicast packet per every *three* packets generated. However, instead of comparing the two multicast architectures with the same number of active components as in Fig. 1 and Fig. 2, we compare two multicast architectures with the same *intended throughput*. This means for both multicast configurations, only *ten* synchronized packets are generated and sent to each node at every time slot: *four* each to both input fiber ports, and *two* to the add fiber port. Only self-similar traffic is deployed as it is more realistic for network analysis.[12–14]

The results are shown in Fig. 7. We observe that when both input fiber ports receive multicast packet, the performance of the feedback configuration become much worse, while the feed-forward configuration can still retain almost the same position for the PLR, and a slightly degraded NT. The NT degradation is caused by the almost doubled amount of multicast packets. As the available external wavelengths at the output fiber remains the same, it is not possible for the node to successfully deliver all the duplicated packets. From Eqs. (2) and (3), we can also expect a lower NT when more input ports are configured as multicast ports.

Fig. 7 also indicated that under such conditions, `Multicast2` without any CR strategy can already achieve similar results to `Multicast1` with `WC` and `WCFB` in both PLR and NT simulations. The large PLR obtained for the `Multicast1` is due to the fact that it can process only *one* multicast packet per time slot, unless more feedback circuits are added, which means more active components and physical resources as well as node internal wavelengths. On the other hand, the feed-forward node can process as many multicast packets as needed in each time slot, as the multicast function is integrated inside each AOLSW.

4. CONCLUSIONS AND FUTURE WORK

In this paper, traffic performance analysis of various AOLS node unicast and multicast architectures are presented. Bernoulli and self-similar traffic driven simulation results are presented under three CR conditions: `NoCR`, `WC` and `WCFB`. We evaluate two parameters: PLR and NT, which represent network reliability and utilization, respectively.

The investigated AOLS node architecture performs best when configured as a unicast switch. With multicast traffic, the feed-forward multicast structure is significantly more efficient than the feedback multicast structure, with both Bernoulli and self-similar traffic. The feed-forward multicast node can achieve comparable performance to a unicast switch of the same dimension. The performance difference between the feedback and feed-forward schemes become more prominent as the number of input fiber ports increases, and as number of the multicast ports increases.

AOLS[2,6,8] and OLS[4,5] technologies are believed to be the future of optical packet switched networks[1] for fiber line-rate data communications. With the increasing amount of multicast applications such as multimedia streaming, high-definition TV, multi-party online games, video conference and optical storage area networks, multicast capable AOLS and OLS switches are important and exciting research topics that are likely to become essential for the transition towards the next generation optical Internet and telecommunications infrastructure. The new constraints and realities imposed by the optical layer and WDM technologies will certainly affect our long-held assumptions that have been developed for mostly opaque optical networks. Switching and multicasting at the optical layer will eliminate the electronic bottleneck for a truly transparent optical network taking full advantage of the available fiber bandwidth, towards future bit-rate, protocol and modulation format independent optical highway.

To this end, ongoing studies on network traffic performance of the AOLS multicast applications are being carried out. Two lines of future research are assessing the node performance on different traffic conditions under various AOLS dimensions and structures, and network performance evaluation of mixed AOLS unicast and multicast nodes in ring and mesh topologies.

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