A Dynamic Optical Packet/Burst-Switched Metropolitan Area Network

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The development of key technologies for high-capacity optical transmission has made possible transmission experiments with very high data rates and a large number of wavelength channels. Based on the recent development of enabling technology, optical network functionality has made progress from simple point-to-point wavelength division multiplexed (WDM) links to automatically switched optical networks. In the future, dynamic burst-switched and packet-switched photonic networks may be expected. This paper summarizes recent research progress in the area of optical metro networks and proposes an architecture for a transparent WDM metropolitan area network that enables switching on both packet-by-packet and burst-by-burst basis, thereby having the potential to achieve high throughput efficiency. The optically transparent MAN also includes a large part of the access network infrastructure. It is scalable, flexible, easy upgradeable and able to support heterogeneous network traffic.

Keywords: **Metropolitan area network (MAN), wavelength-division multiplexing (WDM), optical burst switching (OBS), optical packet switching (OPS), network architecture.**

Ein Dynamisches Städtisches Netz Basierend auf der Optischen Paket/Burst-Vermittlung.

Die rasante Entwicklung der Schlüsseltechnologien für die optische Signalübertragung hat Übertragungsexperimente mit einer sehr hohen Datenrate und einer hohen Anzahl an Wellenlängenkanälen ermöglicht. Basierend auf der Entwicklung der Technologien für Übertragung und Verarbeitung von optischen Signalen wurden auch Fortschritte im Bereich der Netzfunktionalität verzeichnet. Die Funktionalität und Topologie von optischen Netzen hat sich von anfangs einfachen Punkt-zu-Punkt WDM-Verbindungen bis zu automatisch geschalteten Netzen entwickelt. In der Zukunft wird eine weitere Entwicklung in die Richtung dynamischer burst- und paketvermittelten photonischen Netze erwartet. In diesem Artikel, aktuelle Forschungsaktivitäten im Bereich der optischen Metro-Netze werden präsentiert und ein neuartiges transparentes optisches Netz für den städtischen Bereich vorgeschlagen. Dieses Netz ermöglicht sowohl Packet- als auch Burst-Vermittlung in der optischen Domäne und bietet potenziell hohe Effizienz im Bezug auf Datendurchsatz. Es beinhaltet auch ein Teil des Zugangsnetzes, ist flexibel, skalierbar, leicht erweiterbar und unterstützt unterschiedliche Datenformate.

Schlüsselwörter: **Städtische Netze, Wellenlängenmultiplexverfahren, optische Burst-Vermittlung (OBS), optische Paket-Vermittlung (OPS), Netzarchitektur.**

1. Introduction

Optical fiber-based technology for telecommunications applications will continue to play a significant role in the development of an advanced, high-capacity network infrastructure. Nowadays, nobody can imagine a wide area, a regional or a metropolitan area network without optical transmission systems. Mostly, these networks make use of dense wavelength-division multiplexing (DWDM) technology and optical amplifiers to transmit a large number of wavelength channels over large fiber spans. Although such a circuit-switched network infrastructure can provide a large capacity and robustness, it suffers from poor bandwidth efficiency because of the static or semi-static bandwidth assignment per wavelength. This coarse granularity and a slow response on change of bandwidth demand per user do not reflect the needs of modern telecommunications applications. In current data centric networks, bursty traffic is becoming predominant and network operators should be able to provide users with high-quality services and high bandwidth on demand exploiting the potential for statistical multiplexing in the time domain. Future telecommunications applications require a dynamic, high-capacity optical network with the capability to carry heterogeneous network traffic. A finer bandwidth granularity and a faster response to traffic variations than in circuit-switched DWDM networks can be achieved by employing optical packet switching (OPS) [Wada, 2001- Aleksić, 2003] or optical burst switching (OBS) [Rosberg, 2003 – Dolzer, 2001]. The main advantage of those techniques is an improvement of bandwidth utilization through limiting the wavelength occupation time by a single connection, thereby gaining increased wavelength utilization from statistical multiplexing directly in the optical layer.

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In the last few years, a large penetration of optical transmission technology into access and local networks can be observed, especially in the urban areas. The capacity of current local area networks has been rapidly increased by employing advanced network technologies such as Gigabit Ethernet (GbE) and 10 GbE. The access bottleneck has been reduced by introducing various fiber to the home/curb/subscriber implementations in conjunction with wireless access services such as universal mobile telecommunications system (UMTS) and wireless local area networks (WLANs). Storage-based technologies and protocols such as Fibre Channel, ESCON, FICON, FCIP, and iSCSI have also to be considered when talking about heterogeneity of data traffic and protocols that need to be supported by optical backbones.

The role of metropolitan area networks (MANs) is to interconnect high-speed DWDM backbone networks with access networks in order to provide a high bandwidth to heterogeneous customers and to support business to business solutions (e.g. distributed storage and enterprise networks). The future MANs have to be able to provide high capacity while maintaining efficiency and flexibility that are required to handle heterogeneous traffic. Besides that, they should be upgradeable in a modular way, transparent to multiple legacy services/protocols, and highly reliable. A significant research effort has been put recently into development of new architectures and protocols for optical metropolitan area networks. Several different ring-based architectures for advanced optical metro networks have been proposed and investigated [Yao, 2001 - Chlamtac, 1999]. Wavelength allocation and access to the media range from static wavelength-routed optical network (WRON) over static slotted ring (SR) architectures to dynamic optical burst switched and optical packet switched networks. In WRON architectures, lightpaths established between network nodes are allocated to accommodate the traffic demand matrix. This is a static network with zero blocking, underutilizing resources at low loads and a traffic matrix that needs to be known a-priory. In static SR architectures, wavelength channels are slotted and multiplexed in time. Wavelength channels thus may be shared over different connections, i.e., node pairs. Similar to WRON, in a SR network we also need to know the traffic matrix a-priory. It is a static network with zero blocking providing a finer granularity to assign traffic flows compared WRON.

Dynamic optical burst switched (OBS) networks can implement a one-way resource reservation scheme without acknowledgement or an end-to-end reservation scheme with acknowledgement. The first option typically uses either the just-in-time (JIT) or the just-enough-time (JET) resource reservation technique. Here, a burst can be dropped at a traversed node due to contention. Consequently, wavelength conversion is essential in order to decrease the probability of contention. In an OBS network with reservation acknowledgment, reservation of an end-to-end lightpath has to be acknowledged before transmission of the data burst. Since the end-to-end resources are reserved a-priory, lossless transport and end-to-end delay can be guaranteed. Consequently, quality of service (QoS) can be provided.

An alternative to OBS networks using switching in the wavelength domain is to use switching in the time domain. In this approach, named time sliced optical burst switching (TSOBS), the wavelength channels can be organized into a series of frames, each of which is sub-divided into fixed length timeslots [Ramamirtham, 2003]. The equidistant time slots at a fixed position within successive frames form time-division multiplexed TDM channels, which are then used to transmit data bursts over a number of frames. The key building blocks of TSOBS routers are so-called optical time slot interchangers (OTSI), which provide the required time-domain switching for all wavelengths. Due to the fact that switching is done in the time domain rather than the wavelength domain, there is no need for wavelength converters. This is the main advantage of the TSOBS approach.

Switching packets directly in the optical domain is an attractive solution for future high-capacity, dynamic metro networks combining the benefits from packet flexibility and optical transparency. Optical packets provide a good way to integrate efficiently different layers and to reduce the network operating cost. However, the enabling technology for ultrahigh-speed all-optical packet switching is either not commercially available today or very complex and expensive. Therefore, a combination of optical packet and burst switching based on commercially available components could be a good choice for a dynamic and efficient high-capacity optical MAN.

In this paper, we propose a WDM based metropolitan area network with a double counter-rotating ring structure and optical packet/burst switching. It comprises edge nodes fully transparent to data rate and format of the access traffic. The network nodes can be implemented using commercially available components only. Because of its transparency and time-slotted data transmission on every wavelength channel, the network is flexible and can be easily upgraded step-by-step. The end-to-end delay through the entire network can be guaranteed by a-priory reserving a feasible number of consecutive slots. For isochronous time-critical multimedia data-streams, equidistant slots can be reserved by the master node during the connection setup.

2. Network Architecture

The proposed network consists of a central dual counter-rotating WDM ring and M metro edge nodes connected to the concentration units (CUs) that are located in the access area, i.e., represent the optical line terminals (see Fig. 1).

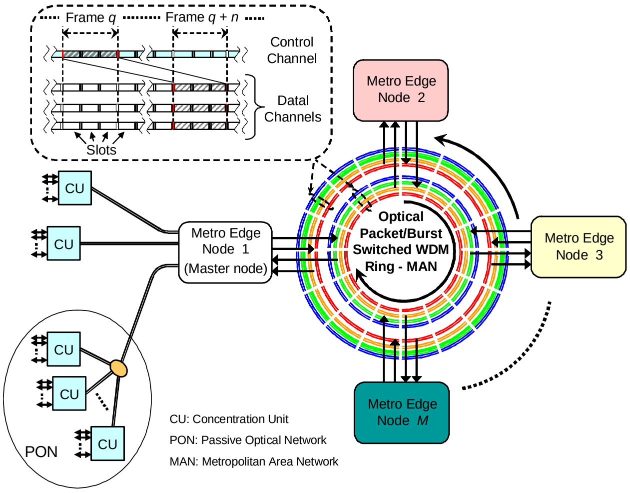

Figure 1: Optical packet/burst switched metro network based on a double counter-rotating slotted-ring topology.

Each fiber ring carries W time-slotted wavelength channels. One of the channels is dedicated to transmission of control and configuration information as well as to serve synchronization of all edge nodes to a central slot clock generated by the master node. Additional to the generation of the slot clock, the master node is also responsible for frame creation, (re-) configuration and slot reservation for isochronous data transmission. Note that every metro edge node is able to act as a master node in the case of a failure in the current master node. In this case, other edge nodes will not receive the slot clock from neither ring and a procedure for selection of a new master node will automatically start.

Edge nodes are basically nothing more than transparent optical switches. Only the control channel is terminated and processed by every edge node, while data channels are switched and forwarded to the concentration units that are capable of transmitting and receiving data slots. The CUs comprises either tunable or fixed transceivers. Low-cost units equipped with fixed transceivers are capable of receiving/transmitting on a single wavelength only, and consequently, they are disadvantaged in comparison to the high performance units equipped with tunable transceivers. If needed, low-cost concentration units can be updated from the single-wavelength to a multi-wavelength version without any significant change in the network. New configuration data for this particular unit have only to be broadcasted to all edge nodes.

The concentration units need to be synchronized to the ring slot clock in order to be able to transmit data in a particular time slot. The slots are grouped into frames of identical length in both control and data channels. The occupation of a slot is indicated in the frame q of the control channel that precedes the data frame containing the particular slot (frame $q + n$). An edge node can reserve a free data slot by indicating it in the corresponding slot of the control channel. The occupation is done after collecting transmitting requests from all CUs connected to the particular node. Note that not only a single slot but also a number of consecutive slots can be reserved in order to transmit a data packet or a burst that exceeds the size of a single slot. Unlike the TDM approach in TSOBS, a single data burst can not occupy slots in more than one frame. The time between the slot reservation in frame q of the control channel and the actual data transmission in the corresponding slot of frame $q + n$ on the according data channel is needed to inform the requesting CU about the successful slot occupation and to give the CU enough time to prepare timely accurate sending of its data in the correct slot also taking into account the signal propagation delay in the fiber connecting the CU and the edge node.

Because of the time-slotted data transmission and the centralized media access control in the upstream direction, a TDMA-based passive optical network (PON) can be directly attached to a port of an edge node. A WDM PON access infrastructure can also be integrated. That is, not only point-to-point but also point-to-multipoint connections can be established between an edge node and concentration units, which makes the network architecture even more flexible.

3. Node Architecture

The architecture of edge nodes for the proposed optical MAN is shown in Fig. 2. It consists of a transparent optical packet/burst switch and two units for synchronization and processing of control channels received from the two counter-rotating rings. The control channels are terminated at every node. They are dropped by using fiber Bragg gratings (FBGs) and circulators, then received by fixed receivers, modified at the node, and finally, forwarded to neighboring nodes by using fixed transmitters and WDM couplers. The slot clock is extracted from both control channels and used to synchronize all the concentration units (CUs) attached to this node. The node indicates slot occupation in a control frame according to the transmission requests from CUs and sends the modified control frame to the next edge node. This is the main task of the metropolitan area part of the media access control unit (Metro MAC). The variable optical delay, τ, has two functions. The first one is to compensate for the control channel processing latency at the node. The second one is to ensure that the frames from both rings arrive at the same time at the node switch.

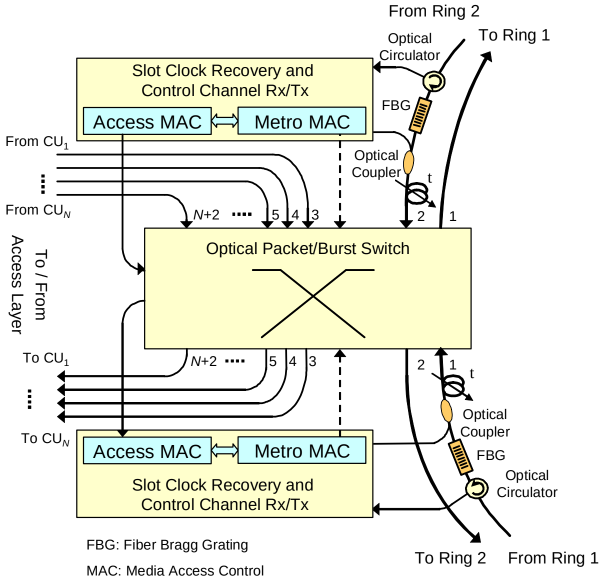

Figure 2: Architecture of the metro edge node.

The access MAC module is responsible for synchronization and coordination of data transmission to and from concentration units (CUs). The whole communication between the access MAC and CUs is done over an access control channel, which also has a slotted structure directly corresponding to the structure of the control channel on the metro rings. The module first collects requests for data transmission from the CUs, and then, after the slot reservation in the ring control channel has been done by the Metro MAC module, it forwards the results of the slot occupation in data frame $q + n$ via the access control channel to the CUs acknowledging the requests. CUs aggregate the traffic received from a number of users, perform burst assembly and send optical bursts or individual optical packets to the metro edge node after receiving a confirmation of successful resource reservation from the edge node. The Access MAC module is also responsible for collecting and forwarding the configuration data to and from CUs. The CUs need to be synchronized to the ring slot clock. For this purpose, every CU needs, in addition to the extraction of the slot clock form incoming control frames, also to measure the time needed for signal propagation from the edge node to the CU and for processing of the control frame. These time delays need to be taken into account when calculating the exact timing for data transmission that must fit in the specific slot on the metro ring. Note that metro edge nodes extract the slot clock from the control channel electronically. There is no need for all-optical clock recovery.

The first two input/output ports of the optical packet/burst switch are connected to the two counter-rotating metro rings, while the residual N ports are used to attach concentration units to the edge node and to send/receive the access control channel. Similarly to the ring control channels, also the access control channel is separated from data channels before entering the switch by means of FBGs and circulators (see Fig. 3). The access control channel is added to the output ports connected to CUs by using WDM couplers. The ring ports have a higher priority than access ports. That is, the connections through the switch for a particular time slot are first determined for ring data traffic and after that for access data traffic upon availability. If a connection for transmitting access data in a time slot is not possible, a negative acknowledgment is sent back to the requesting CU, which can again request for data transmission in the next reservation cycle. Thus, due to the fact that data is transmitted only if the result of the distributed resource reservation procedure is positive, there is no packet or burst loss in the network. However, if a packet is lost because of overflow in the CU's transmitting buffer, the retransmission will be provided by higher layers. In order to support high-priority isochronous data transmission, the master node can reserve a number of equally spaced time slots in each frame for a single end-to-end connection after a previous request during the connection setup.

The structure of an optical packet/burst switch is shown in Fig. 3. It consists of $2\cdot(N+2)$ passive optical couplers/splitters and $(N+2)^2$ wavelength selective modules (WSMs). In each WSM, the incoming WDM signal is divided into W single channel paths by using a WDM demultiplexer. The wavelength channels are selected using semiconductor optical amplifiers (SOAs). Only the channels, for which SOAs are set in the "ON" state by applying a current to them, pass the device. The selected channels are then collected at the output of the WSM by using a WDM multiplexer. We consider the deployment of gain-clamped SOAs (GC-SOAs) because of their large input dynamic range in comparison to conventional SOAs. They can also be used to amplify the signal, thereby compensating for losses in optical couplers/splitters and WDM multiplexers/de-multiplexers. The switch is basically implemented as a broadcast-and-select architecture, so that wavelength channels from any input port can be forwarded to any output port. A single wavelength channel from a particular input port can also be selected to be forwarded to more than one output port simultaneously, thus, multicasting by copy&forward can easily be supported directly in the optical domain.

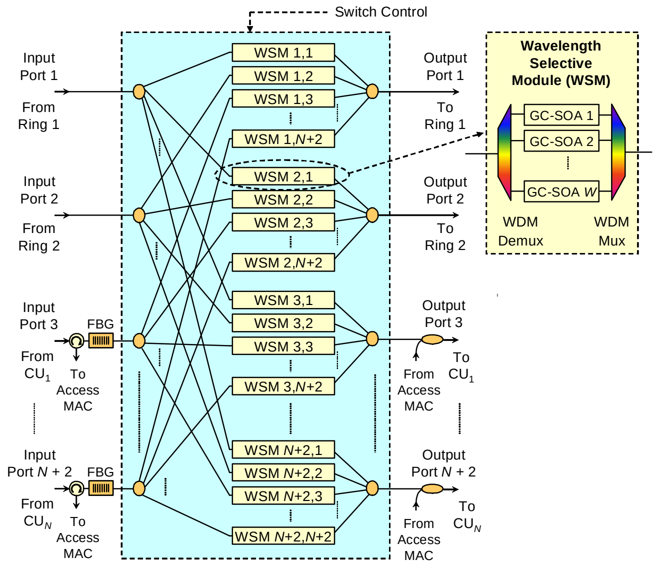

Figure 3: A broadcast-and-select optical packet/burst switch (W wavelength channels, $N+2$ ports).

4. Frame Format

The structure of data and control frames is shown in Fig. 4. Both data and control frames are divided into j slots. The start and the end of a frame are indicated by a frame delimiter in the control channel. The time slots are separated by slot delimiters, which can be used to extract the slot clock. Connections through the switch can be rearranged at the start of every slot. There are guard intervals inserted immediately after slot delimiters in order to provide enough time for a clear change of the switch configuration between any two time slots, i.e., to avoid signal degradation caused by transitional effects in the SOAs and by the finite response time of the control circuitry. This makes possible switching of single packets or data bursts. Packets smaller than or equal to the slot length are easily transmitted by occupying a single slot. Long packets or data burst are transmitted as a continuous data block by occupying a number of consecutive slots. In this case, there is no need for guard periods between slots during the packet/burst transmission, which improves significantly the transmission efficiency.

The occupation of data slots is indicated in the control frame. Each slot of a control frame q is divided into W fields of which the first field is used for configuration as well as for operation, administration and maintenance (OAM) information, while the residual $W-1$ fields are used to indicate the status of the corresponding time slot in the frame $q+n$ on the $W-1$ data channels. That is, the control frame precedes the data frame for a number of frames, n, which is chosen such that edge nodes have enough time to inform the concentration units about successful slot occupations and to leave the CUs enough time to timely transmit their data in the specified time slot. The $W-1$ channel occupation fields contain destination address (DA), source address (SA) and the length in slots of the data packet or burst that is going to be transmitted over this channel. The reserved part of the channel occupation fields can be used for communication between edge nodes and the master node, for example to request reservation of resources for isochronous transmission. There is an additional field of the length of 4 Bytes in every of the $W-1$ channel occupation fields of the first slot that carries a slot occupation table (SOT) for the corresponding channel. Each of the SOT field bits represents occupancy of a slot in the particular channel, i.e., logical 1 means that the particular slot is occupied and logical 0 that it is free. The complete SOT indicating status of all slots in a frame at $W-1$ data channels is thus received during the first slot, which allows a significant reduction of the control channel processing delay.

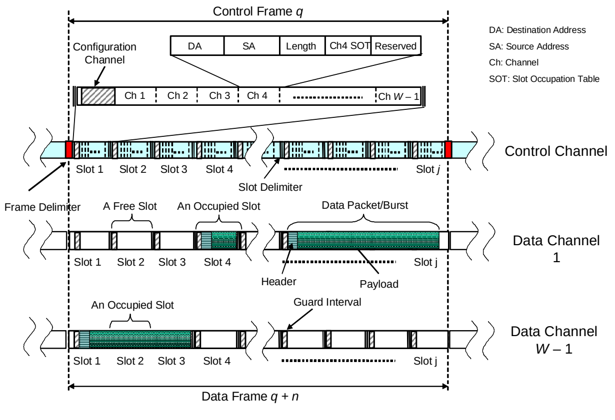

Figure 4: Format of data and control channel frames.

A CU can request a single slot or a number of consecutive slots for transmission of a packet or data bus in data frame $q + n$ by indicating it in the corresponding slot of the access control frame q. For this purpose, there are $W - 1$ Req. fields in every slot of an access control frame (see Fig. 5a). The Req. fields contain source and destination addresses of the requested transmission as well as a Req. Length field and a Req. # field. These fields are contained in every slot of the control frame. Fig. 5b shows format of the control channel in the access area that is transmitted from a metro edge node to the CUs attached to this particular edge node. The structure of the access control frame is similar to that of the metro ring, but instead of the SOT field there is an Ack. # field, which can be used to acknowledge a CU's request to send data in frame q + n of the corresponding data channel. The Ack. # field is contained in every slot of the control frame.

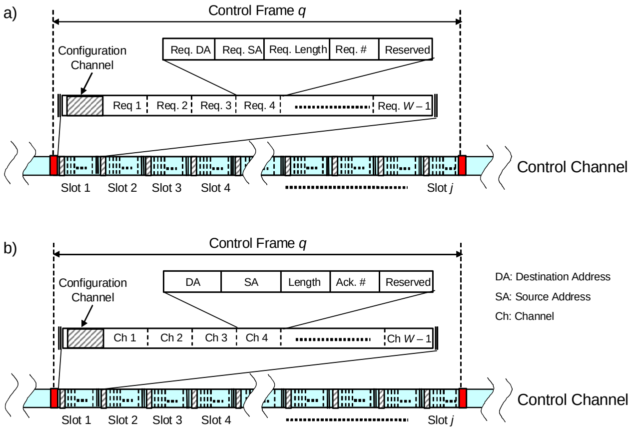

Figure 5: Structure of the access control channel: a) from CU to metro edge node and b) from metro edge nodes to CUs.

The format of all address fields is identical. The first bit (bit 0) is an I/G flag showing if the address is an individual (unicast) or a group address (multicast). The bits 1 to 8 carry a metro edge node address. By using the 8 bit addresses it is possible to address up to 256 edge nodes. The residual 15 bits (bits 9 to 23) are used to address a particular CU. The CU address space is large and can support up to 32,768 CUs.

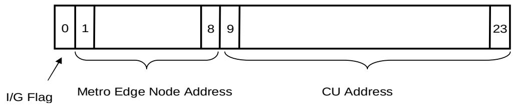

Figure 6: Format of the address fields.

The frame length, slot size and number of wavelength channels are design issues. However, the frame should be equal or larger than the max. burst size of the system. The guard intervals should be larger than 10 ns, in order to allow switching transients to die away.

The network is transparent with respect to data rate, so that any rata rate and modulation format can be supported. However, optical signals at different data rates and using different modulation schemes will be unequal affected by different effects during its propagation through the network elements. Therefore, we investigated the transmission performance of the proposed metro edge nodes for two different data rates of 10 Gbit/s and 40 Gbit/s and the non-return-to-zero modulation format, which are the most likely to be used in such a metropolitan area network. Some results of this study are shown in the next section.

5. Transmission Performance

Optical splitters, couplers, filters and other components of the optical packet/burst switch induce losses that need to be compensated by optical amplifiers. The higher the splitting factors of optical splitters the larger the insertion loss of the switching fabrics, and consequently, an optical amplifier with a sufficiently high gain is needed to compensate for the high insertion loss. This amplifiers as well as SOAs add amplified spontaneous emission noise (ASE) to the signal, which causes a degradation of the optical signal to noise ratio (OSNR). Additionally, wavelength selective components (WDM Mux and Demux) influence spectral characteristics of the signal at switch outputs. Gain dynamics and nonlinear effects in optical amplifiers further contribute to signal degradation. All these effects may limit the scalability and cascadability of the metro edge nodes.

In order to determine scalability of the optical packet/burst switch, which is the main part of the metro edge node, we generated a dense wavelength-division multiplexed (DWDM) signals at 10 Gbit/s and 40 Gbit/s in our simulation setup. The separation of wavelength channels was chosen to be 100 GHz according to ITU-T grid with the central channel at λ_{center} = 1552.52 nm. All data channels were generated by using non-return-to-zero (NRZ) modulated pseudorandom bit sequences (PRBS). We modeled a single signal path through the switch by taking into account all relevant effects such as losses, noise sources, nonlinear effects and crosstalk originating from neighboring channels. The simulation setup and a more detailed listing of main parameters used in simulations can be found in reference [Aleksić, 2007].

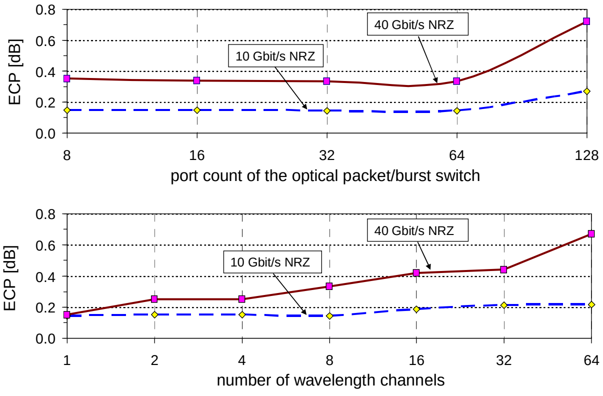

Figure 7: Eye closure penalty (ECP) for various switch sizes from 8 × 8 to 128 × 128 and for different numbers channels.

Fig. 7 shows scalability of the optical packet/burst switch regarding both number of wavelength channels and number of ports. It can be observed that eye closure penalties (ECP) below 0.5 dB were obtained for both 10 Gbit/s and 40 Gbit/s non-return-to-zero (NRZ) modulated signals and for switch sizes up to 64 × 64 ports and up to 32 wavelength channels per port. For a higher port count and a larger number of channels, the ECP increases up to 0.27 dB and 0.72 dB for 10 Gbit/s and 40 Gbit/s signals, respectively. Thus, the proposed architecture of metro edge nodes features a scalability regarding both number of CU ports and number of WDM channels, which is large enough for application in metropolitan area.

6. Summary and Conclusions

In conclusion, the paper reviews advanced architectures protocols proposed recently for dynamic optical metropolitan area networks. Particularly, a novel architecture of optical packet/burst-switched metro network is introduced. The main part of the network is an optically transparent metro edge node. It enables a dynamic, reliable, high-speed, and low-delay data transmission over the entire network. This paper describes network and node architectures as well as some details of the appropriate media access control (MAC) protocol. It also presents preliminarily results of our transmission performance study. Through merging the metropolitan area network with a large part of the access network infrastructure it becomes possible to move the data processing complexity from metro edge nodes to concentration nodes that are located close to the end users. This architectural model has a large potential to improve reliability, flexibility and throughput efficiency of both access and metropolitan parts of the network.

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