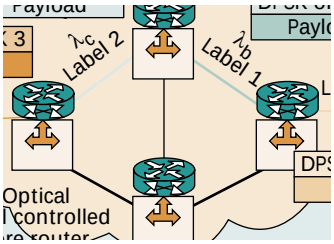

STOLAS: SWITCHING TECHNOLOGIES FOR OPTICALLY LABELED SIGNALS

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ABSTRACT

GMPLS-based labeled optical burst switching (LOBS) networks are being considered as the next-generation optical Internet. GMPLS includes wavelength switching next to label and fiber (space) switching. In this article, we present a new concept of optically labeling bursts of packets suitable for LOBS networks supported by the GMPLS protocol. It is based on angle modulation, which enables control information to modulate the phase or frequency of the optical carrier, while payload data are transmitted via intensity modulation (IM). In particular, the optical label is orthogonally modulated, with respect to the payload using either *frequency shift keying* or *differential phase shift keying*. We present a performance analysis of the aforementioned modulation schemes by means of simulations where the influence of the payload IM extinction ratio and laser linewidth are investigated. In addition, the transmission performance of an IM/FSK combined modulated signal is experimentally validated at 10 Gb/s, demonstrating at the same time FSK label swapping operation. Finally, a suitable optical label-controlled switch design is proposed that takes advantage of these novel labeling techniques, and efficiently combines widely tunable, fast switching lasers and SOA-MZI wavelength converters with an arrayed waveguide grating router.

INTRODUCTION

Wavelength-division multiplexing (WDM) technology has reached a mature phase of development and has opened the way to exploit the vast bandwidth of optical fiber links. Although terabit line rates can be achieved in WDM transmission links, current switching technologies are capable of switching at rates of "only" 1–10 Gb/s. While emerging asynchronous transfer mode (ATM) switches and IP routers can be used to switch data using the individual channels within a WDM link (the channels typically operate at 2.4 or 10 Gb/s), this approach implies that tens or hundreds of switch interfaces must be used to terminate a single link with a large number of channels. Moreover, there can be a significant loss of statistical multiplexing efficiency when the parallel channels are used simply as a collection of independent links, rather than as a shared resource. As networks evolve to data-centric ones dominated by traffic of IP packets, the discrepancy between the low switching speed of the routing nodes and the high transmission rates over WDM links undermines the efficiency of optical networks. Optical packet and burst switching [1–3] has been introduced as the main concept to overcome these limitations and fully exploit bandwidth capacity, in a cost effective way, *taking advantage of statistical multiplexing*, in the sense that packets make on-demand use of the outgoing capacity. Statistical multiplexing is especially useful to cope with the bursty nature of traffic, which is a typical characteristic of data-centric networks. This is in contrast to time-division multiplexing (TDM) circuit switches that assume regular periodic traffic and fixed allocation of packet slots to circuits. Optical burst switched networks represent a trade-off between circuit and packet switching where generalized multiprotocol label switching (GMPLS) can provide an effective IP over DWDM networking [2, 4]. Optical burst switching (OBS) enables quick and efficient forwarding of IP packets because it uses only a single forwarding algorithm based on optical label swapping (removal and reinsertion). The optical label is a short fixed-length value attributed to each IP packet or forwarding equivalence class (FEC) and used to forward the packet or burst through the network. It can be bit serial or parallel multiplexed with the payload data [5, 6]. Parallel multiplexing techniques are more promising and yield significant advantages when applied to optical packet bursts, since the label data, which is at a significantly lower rate than the payload, can easily be separated from the payload by using either the frequency domain or, as we shall show in the present article, a modulation format orthogonal to that of the payload.

In this article we present two novel optical labeling techniques suitable for GMPLS-based LOBS networks developed within the framework of the Switching Technologies for Optically Labeled Signal (STOLAS) project. The scope of the STOLAS project is to develop labeling techniques that will allow routing/switching technology to scale to terabit rates and furthermore to demonstrate routing/switching of bursts of

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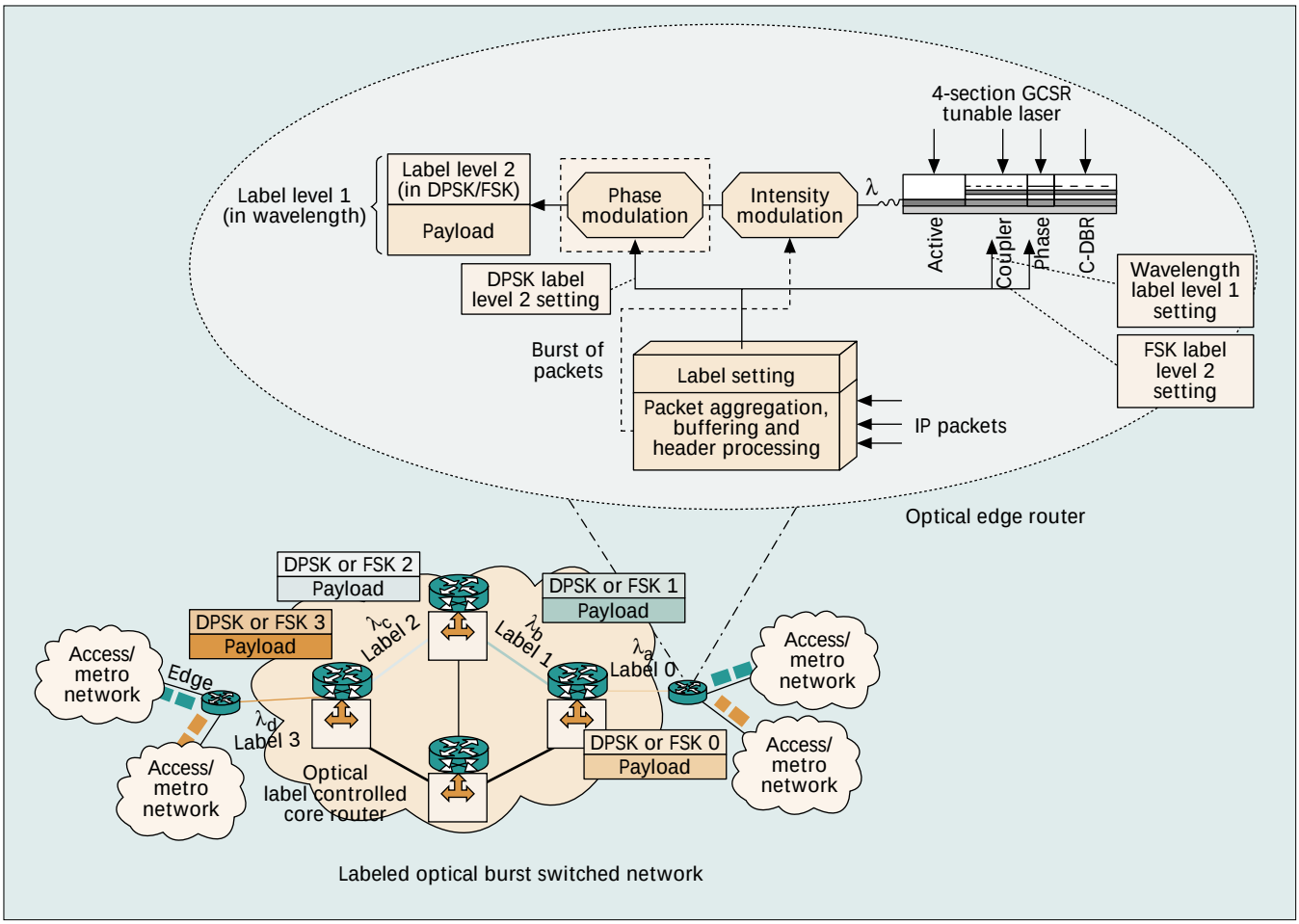

FIGURE 1. Two-level IM/DPSK or IM/FSK optical labeling at an edge router.

packets based on optical label swapping. Partners contributing to the project are Bell Laboratories (The Netherlands), Technical University of Eindhoven (The Netherlands), University College Dublin (Ireland), IMEC (Belgium), Research Center COM (Denmark), Telenor (Norway), and HYMITE (Denmark). The proposed labeling techniques are based on orthogonal modulation of the label information with respect to the intensity modulation format of the payload. In particular, label data are encoded using either *frequency shift keying* (FSK) or *differential phase shift keying* (DPSK). At each network node, the labels are inspected and the appropriate optical path is set, through which the burst payload data is forwarded transparently. A key building block for the implementation of the aforementioned optical labeling techniques is the label swapper module that is commissioned to extract and reinsert the optical labels from each incoming burst. Within the framework of the project, label swappers employing widely tunable grating co-directional coupler sampled grating reflector (GCSR) or sampled grating distributed Bragg reflector (SG-DBR) lasers in combination with a semiconductor optical amplifier (SOA)-based Mach-Zehnder interferometer (MZI) wavelength converter, will be developed.

The article is organized as follows. We present a brief overview of various burst/packet switch designs already reported. The STOLAS label-controlled switch architecture, suitable for the proposed optical labeling schemes, is then described. Results of a numerical comparative study of the combined IM/FSK or IM/DPSK modulation schemes are presented, while we then report an experimental validation of the transmission performance of an IM/FSK signal, together with label swapping at 10 Gb/s. It is worth noticing here that IM/FSK is the preferred implementation option in the STOLAS project due to the simple and robust implementation of wavelength-tunable optical FSK transmitters.

All Optical Burst/ Packet Switch Architectures

In GMPLS-based LOBS, bursts can be composed by assembling several IP packets (in ingress LOBS nodes) and may contain several megabytes of data. For example, at the edge of a transport network, the packets from an access (or metropolitan) network, are aggregated into bursts, buffered, and assigned a header, in an edge router. This header contains routing information, in a similar way to the electronic label switched paths (LSP) in the MPLS protocol. The burst is then transmitted using a certain (preconfigured) wavelength channel. At each node, the optical label is inspected, modified, or replaced, and the burst is routed to the appropriate output. For optical burst or packet-switched networks, several innovative burst/packet switch architectures have been proposed in the literature such as the staggering switch [7], the switch with large optical buffers [8], the wavelength routing switch, and the broadcast-and-select switch [5]. Switches with recirculating loops were the first optical packet switches to address the high-bandwidth and buffering issues. This solution, however, increases the complexity of the switch block, since for an $N \times N$ switch with L delay lines for buffering, an $(N + L)((N + L)$ space switch is required instead of an $N \times N$. The staggering switch was the first optical switch designed

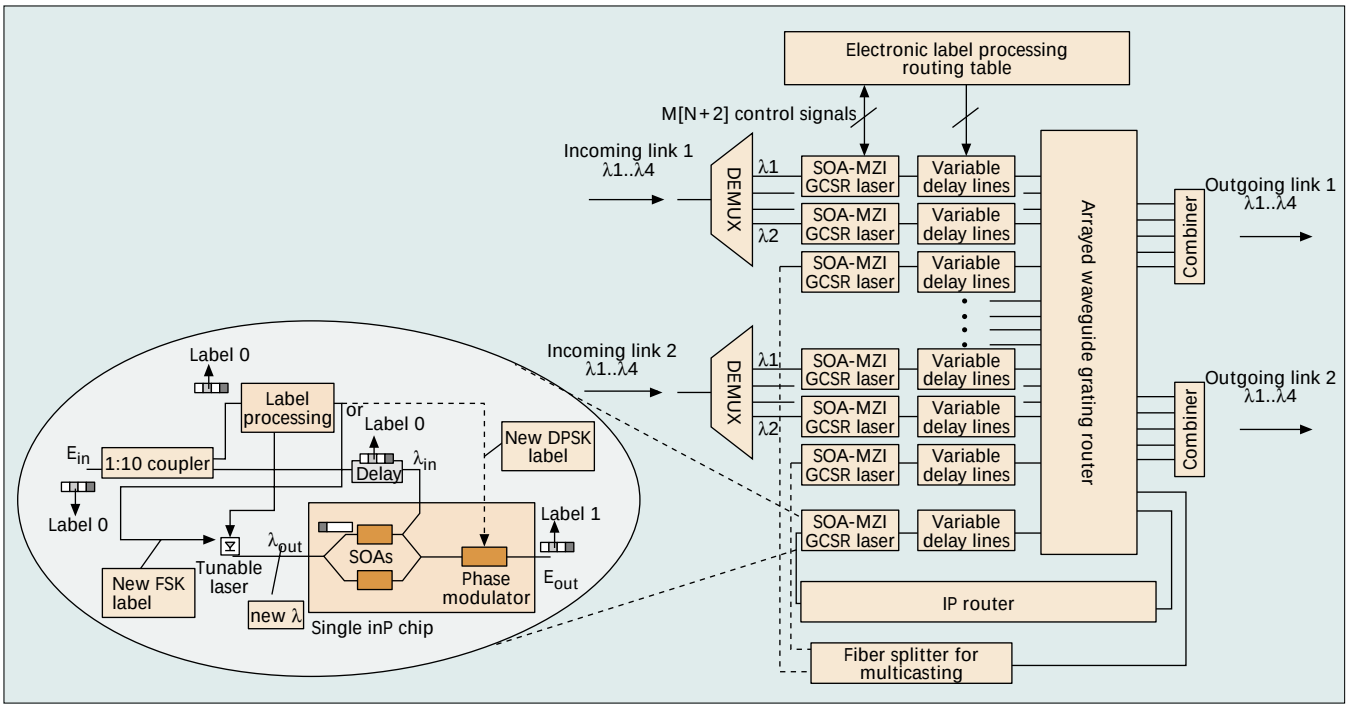

FIGURE 2. An optical label-controlled switch and optical label swapper for DPSK or FSK label format.

to truly emulate an output-buffered switch. Although very promising and influential, the design has the disadvantage that packets may be unnecessarily delayed, even if there is available capacity on their desired outgoing link, and furthermore exhibits rather poor packet loss characteristics for bursty traffic. The switch with large optical buffers (SLOB) cascades many small output-buffered switches (and therefore has larger cost) to form a switch with a larger buffer depth in order to reduce the packet loss rate for bursty traffic. Renaud *et al.* [5] detail two WDM shared output-buffered packet-switching architectures, called the wavelength routing switch (WRS) and the broadcast-and-select switch (BSS), that were developed through the ACTS "Keys to Optical Packet Switching" (KEOPS) project. The WRS is a two-stage switch that first buffers conflicting packets and routes them to their desired output, where a tunable wavelength converter is used to route packets to the appropriate delay line and output port, respectively. Although the WRS is an improvement compared to the staggering switch by being *non-wasting*, it suffers from scalability and modularity issues. In the BSS, fast SOA gates are used to select the appropriate packets at each output for each time slot. The BSS architecture is one of the few proposed architectures that can easily provide multicasting. In addition, it can be used as the building block in a multistaged switch, in order to allow for a modular growth for up to several hundreds of switch inputs/outputs.

THE STOLAS LABELED–CONTROLLED SWITCH ARCHITECTURE

Within the STOLAS project, an arrayed waveguide grating (AWG)-based label-controlled switch that efficiently integrates widely tunable lasers and SOA-based MZI wavelength converters is developed. Routing is performed based on the attached label information, while switching is performed based on the wavelength, which semantically can be treated as a *label*. An optical edge router is used to aggregate data packets, and determine their wavelength and label data. Figure 1 shows the setup of the optical edge router within a LOBS network that uses DPSK or FSK to encode label information. In particular, it shows a ring network topology, but it can be any kind, including physical mesh topologies. Incoming IP packet or other types of data without synchronous framing are aggregated, and their headers are processed. An appropriate label is determined, and by means of a tunable GSCR laser, the outgoing wavelength is set. FSK modulation with tone spacings compatible with direct detection of the label after optical filtering (typically 20 GHz) can be achieved by modulating the current applied the phase section of the laser. Alternatively, an external phase modulator is required in case DPSK is chosen for encoding the label.

Figure 2 displays the architecture of the STOLAS label-controlled switch. It consists of a set of two-level label swappers followed by an arrayed waveguide grating. A set of variable delay lines is also incorporated, commissioned to synchronize the incoming/outgoing bursts of packets. The architecture has been designed in a way to serve the "stacked" labeling concept. Thus, the incoming bursts are tapped, and the orthogonal label data are extracted and fed for electronic processing. After label inspection, the requested optical path is set, along which the packet payload data are forwarded transparently, by appropriately setting the output wavelength of the tunable laser. To this end, packets can be either dropped or directed to the switch outputs or into feedback fiber loops for buffering or multicasting purposes. Especially in the latter case, bursts of packets are directed via a power splitter back to the inputs of the AWG, from which they can be redirected to the appropriate outgoing fibers. Similarly, in the case of buffering, feedback fibers can be used to temporarily buffer the bursts using either simple fiber delay lines or switchable delay lines. It is worth noticing here that when GMPLS is used to establish label switched paths (LSPs) through the network, the network allows no buffering in its core. Buffering is carried out electronically at the edge of the network. Different service classes can be realized using scheduling at the edge as well as by priority mechanisms within the network. Finally, a set of wavelengths is also reserved for adding packets from a local IP router. New orthogonal modulated labels are reinserted, via the two-level label swap-

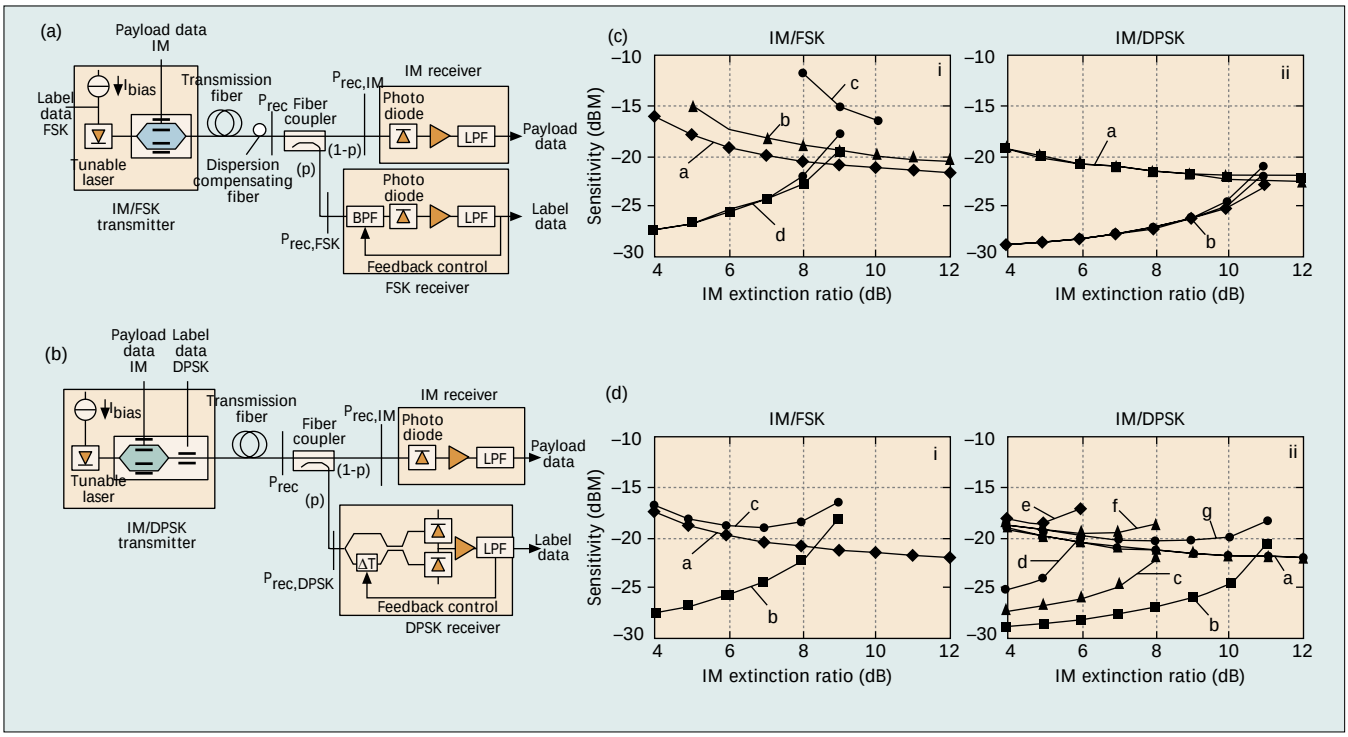

FIGURE 3. A schematic diagram of a) IM-payload/FSK-label and b) IM-payload/DPSK-label transmission link: c) receiver sensitivity vs. payload extinction ratio for various transmission links. (i) IM/FSK combined modulation format {a = 10 km, b = 15 km, c = 18 km for IM, and d = 10, 15, 18 km for FSK}, (ii) IM/DPSK combined modulation format, {a = 20, 40, 60 km for IM and b = 20, 40, 60 km for DPSK}; d) receiver sensitivity change against IM payload extinction ratio for various laser linewidth values. (i) IM/FSK combined modulation format {a = 50, 100 MHz for IM, b = 50, 100 MHz for FSK, c = 50, 100 MHz overall} (ii) IM/DPSK combined modulation format {a = 2.5, 5, and 7 MHz for IM, b = 2.5 MHz, c = 5, d = 7 MHz for DPSK, e = 2.5 MHz overall, f = 5 MHz overall, g = 7 MHz overall)}.

pers, commanded by the routing table. As a rule of thumb, for a switch design handling N wavelengths and having M incoming/outgoing links a $[(M + 2) \times N] \times [(M + 2) \times N]$ AWG is required, as well as $(M + 2) \times N$ label swappers. In such a design, N input ports in the AWG are reserved for adding/dropping packets and N additional ports for multicasting purposes. The same functionality can be achieved in a more modular way (e.g., in an $N = 4$ and $M = 2$ node) by incorporating three 4×4 AWGs or even 2×2 AWGs. The scalability of this AWG node design is limited by the tunability range of the tunable laser source as the number of wavelength increases. An alternative approach for scalability is the use of multistage designs [10]. However, a trade-off should be found between the improved scalability, throughput performance, and switch cost, which is a topic for further consideration. The overall switching time per packet burst depends mainly on the label processing and the wavelength switching time, which in total can be in the order of microseconds. For the compensation of this, a fiber time delay is used within the two-level label swapper.

As mentioned previously, a key component in the node design is the two-level label swapper. Within the STOLAS project, label swappers capable of swapping both the wavelength and orthogonal label are realized. The inset of Fig. 2 shows the details of the label swapper. It consists of a widely tunable GCSR laser and a Mach-Zehnder interferometric structure with two SOAs in its branches. Depending on the label processing result, a new wavelength is set by adjusting the combination of currents applied to the different sections of the GCSR laser diode, and thus the incoming intensity-modulated payload data -after being properly delayed- are transferred to this new wavelength through cross-phase modulation (XPM) in the MZI-SOA wavelength converter. As the XPM mechanism in the SOAs is driven only by the intensity of the incoming packet, the incoming optical DPSK or FSK label is erased. New labels are reinserted, either by means of a phase modulator integrated together with the MZI-SOA wavelength converter, or by modulation of the phase current of the GCSR laser, in the case of DPSK or FSK labeling, respectively. In the latter case, the two-level label swapper circuit is simplified and the function of the tunable laser is twofold: to switch to the new wavelength label as well as to generate a FSK modulated signal. Thus, using a single active device, a tunable optical FSK transmitter can be realized.

OPTICAL LABELING IN LOBS NETWORKS

The advantage of having out-of-band labels on a separate (control) wavelength, as already adopted in [2], is the capability to separate the switching from the control plane, allowing easy label data extraction, detection, and processing, providing a quick and efficient single forwarding algorithm based on label swapping. To this end, label data can be at a significantly lower rate and on a separated frequency from the payload, allowing scaling to terabit rates. Therefore, label processing requirements as well as synchronization between bursts or between bursts and labels can be significantly less stringent. Furthermore, a serious amount of high-speed optical-electrical-optical (O/E/O) converters is avoided, as the payload data remain in the optical domain and are delayed until the end of the electronic processing. Currently, subcarrier multiplexing (SCM) has been the only option investigated for possible implementation of parallel payload label multiplexing [3, 6]. According to this technique, the label information is modulated on an RF signal, generating two symmetrical optical tones around the center optical frequency of the payload spectrum. However, fiber nonlinearities such as cross-phase modulation (XPM) and four-wave mixing (FWM) may generate signifi-

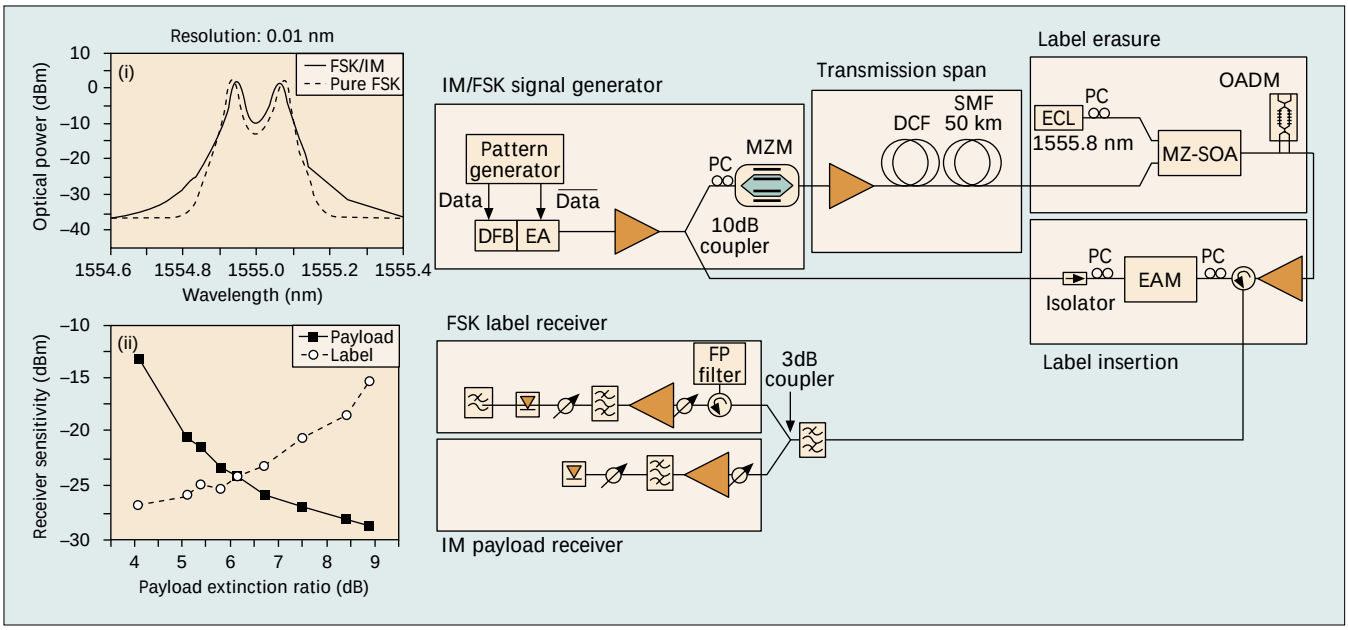

FIGURE 4. Experimental setup for the transmission and label swapping experiment: (i) optical spectra of the FSK and IM/FSK signal; (ii) sensitivity of the label and payload receiver as a function of the payload extinction ratio in the back-to-back case.

cant amounts of crosstalk between adjacent subcarrier labels, due to their small wavelength spacing. Furthermore, fading due to fiber dispersion limits the range where the subcarrier multiplexed label can be detected. In the following section, we assess the performance of FSK and DPSK labeling on the same wavelength as the one used for transmission of the payload data.

The feasibility of combined intensity modulation and angle modulation has been previously demonstrated in an experimental WDM network [9]. However, a coherent detection scheme was employed in those experiments. In the STOLAS project, we focus on angle modulation schemes compatible with direct detection. Therefore, a one-bit delay interferometer can be used to convert the DPSK modulation of the label to intensity modulation, while FSK modulated labels with large tone spacings can be directly detected following an optical bandpass filter. In both cases, detection of the angle modulated label requires optical power to be present at the label receiver even when a "0" payload bit is transmitted, resulting in limitations to the payload extinction ratio. In case a DPSK modulated label is used, the laser linewidth is known to be detrimental to the label detection, especially at low label bit rates. The influence of the payload extinction ratio and laser linewidth is investigated further in what follows.

The performance of both combined modulation schemes has been assessed by simulating transmission links employing direct detection for the IM and FSK data and a balanced detection scheme for the DPSK data. Figure 3a and b show the schematic diagram of the simulated links with the IM/FSK and IM/DPSK transceivers. Direct current modulation of the laser is employed to obtain FSK modulation. In this process, the amplitude of the optical signal may also vary, introducing an unwanted residual amplitude modulation, which might in turn induce crosstalk on the payload that is subsequently modulated with an external Mach-Zehnder modulator. To this end, the effect of residual amplitude modulation due to direct FSK modulation of the laser source is included in the simulations. In both transmission links, the payload data is a $2^{23} - 1$ pseudo random bit sequence (PRBS) pattern running at 10 Gb/s, whereas the label data is a $2^7 - 1$ PRBS at 155 Mb/s. The receiver sensitivity for IM and FSK (or DPSK) is defined as the average received power to achieve a bit error ratio (BER) of 10^{-9} and 10^{-12}, respectively. The BER of the label receiver is required to be much lower than the one of the payload receiver, as routing errors will cause the loss of many packets, whereas payload bit errors may be corrected by upper link layer protocols. The optimum IM extinction ratio is defined as the value that yields the same receiver sensitivity for both modulation formats. When the payload IM extinction ratio is increased, the sensitivity of the payload receiver is improved while the sensitivity of the FSK (or DPSK) receiver is degraded. Figure 3c displays the receiver sensitivity of the IM, FSK, and DPSK receivers as a function of the IM extinction ratio for various transmission lengths over standard single-mode fiber (SMF). In the case of FSK, a tone separation of 20 GHz and an FSK-induced residual intensity modulation of 0.46 dB are assumed. In addition, laser linewidths of 100 and 2.5 MHz are assumed for FSK and DPSK, respectively. From Fig. 3c it can be seen that the IM/DPSK combined format can achieve a transmission distance of 60 km over typical SMF without any significant receiver sensitivity degradation, whereas the IM/FSK scheme is limited to a transmission distance of 15 km. This is due to the dispersion penalty induced on the payload that is modulated over the two tones separated by 20 GHz. The walkoff experienced by the two tones when propagating over dispersive fiber is responsible for intersymbol interference after detection. Therefore, stricter dispersion compensation requirements are to be fulfilled in the IM/FSK case. Alternatively, the use of nonzero dispersion shifted fibers (NZDSF) will allow uncompensated transmission distances to be extended. Nevertheless, dispersion compensation will still be required for typical 80–100 km terrestrial network spans.

In order to assess the influence of the laser linewidth on the transmission performance, we simulated transmission over a 60 km single mode fiber link. For reasons of comparison, 9.6 km of dispersion compensating fiber was added at the end of the link in the case of FSK to compensate for the dispersion of the 60 km standard single mode fiber. Figure 3d shows the calculated receiver sensitivity at the aforementioned BER values, in the case of 50 and 100 MHz linewidth for FSK and 2.5, 5, and 7 MHz linewidth for DPSK. It is evident that DPSK data detection imposes stringent requirements on the laser linewidth, while FSK can tolerate much higher values. The

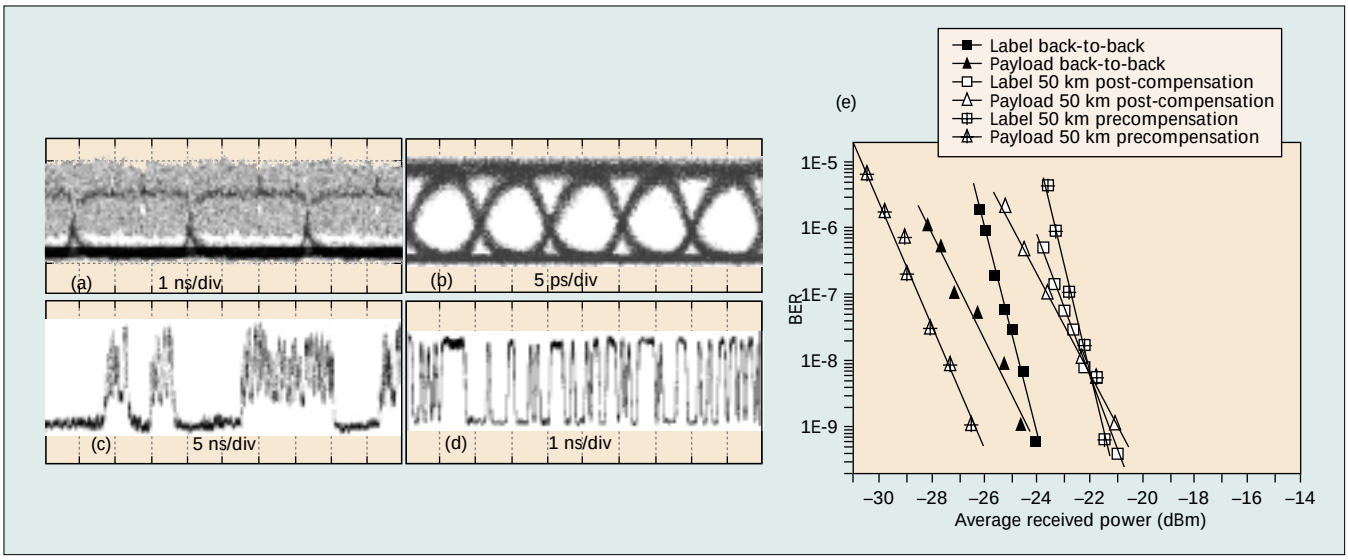

FIGURE 5. a) Received eye diagram of the 312 Mb/s FSK label; b) eye diagram of the 10 Gb/s IM payload; c) received pattern of the label; d) received pattern of the payload; e) bit error rate vs. received power for back-to-back and after 50 km transmission with pre- and post-compensation.

optimum IM extinction ratio for the combined IM/FSK format is in the range between 7 and 8 dB (line c in Fig. 3d(i)), while for the combined IM/DPSK format, values closed to 7 and 8 dB (line g and f in Fig. 3d(ii)), were found for a laser linewidth of 5 and 7.5 MHz, respectively. It should be noticed here that in the case of DPSK, this value depends strongly on the magnitude of laser linewidth. Therefore, we may conclude that IM/FSK offers a significant advantage over IM/DPSK as a payload/label encoding option. Despite limitations imposed by dispersion, its simplicity in terms of creation/detection and laser linewidth requirements makes IM/FSK the preferred implementation option for the STOLAS project. In addition, with an optimized dispersion compensation scheme, extended transmission distances can be achieved. On the contrary, implementation of IM/DPSK requires a Mach-Zehnder interferometer with a one-bit delay at the receiver end, which may severely impact performance due to potential instability, especially at low bit rates compatible with electronic label processing.

LABEL SWAPPING AND EXPERIMENTAL VALIDATION OF THE IM/FSK COMBINED MODULATION FORMAT

Label swapping is the key function in LOBS networks. Depending on the label processing result and the lookup in the routing table, a new label is generated and encoded on the frequency (or phase) of the optical carrier. As already mentioned, label swapping can be performed using a MZI-SOA wavelength converter. Other schemes can be exploited to perform label insertion, such as cross-absorption modulation in an electro-absorption modulator (EAM). In order to demonstrate the feasibility of the STOLAS concept, we report experimental transmission of a 10 Gb/s IM payload orthogonally modulated to a 312 Mb/s FSK label with 20 GHz tone spacing over a 50 km SMF link. Following transmission, label swapping is successfully performed by label erasure in a MZI-SOA wavelength converter followed by label insertion in an EAM. Figure 4 shows the experimental setup used to demonstrate the generation and transmission of the IM/FSK combined modulated signal as well as to demonstrate label swapping, including wavelength conversion. Within the transmitter part, optical FSK modulation is obtained by direct modulation of the electrical current of a DFB laser at 312 Mb/s. In order to suppress the unwanted residual intensity modulation, a subsequent integrated electro-absorption modulator is driven by the inverted label signal with proper delay. The payload is then imposed at 10 Gb/s on the intensity of the FSK signal using a chirp-free Mach-Zehnder modulator (MZM). Inset (i) of Fig. 4 shows the optical spectrum of the directly modulated DFB laser at 312 Mb/s (pure FSK) as well as the IM/FSK spectrum after modulation of the payload. Within the receiver part, the labeled optical signal is split using a 3 dB optical coupler. The output of one arm is directly detected by a photodiode, and thus the optical payload is converted into the electrical domain, while in the second arm a fiber Fabry-Perot filter is used to filter out a single tone of the FSK labeled signal. In the transmission span, two different dispersion compensating schemes have been considered, precompensation and post-compensation, both consisting of 50 km of SMF and the matching length of DCF to fully compensate fiber dispersion. Inset (ii) of Fig. 4 illustrates the relation between the measured receiver sensitivities of the payload and label, and the extinction ratio of the payload in the back-to-back case. The sensitivities are evaluated at a BER of 10^{-9}. From this figure, it is found that a good trade-off between the label and payload performance can be achieved with nearly 6 dB extinction ratio.

Figure 5a–d show the eye diagrams and the patterns of the received FSK and IM optical signal, respectively. In the FSK signal, the upper rail corresponding to the "1" level is thickened due to the influence of the intensity modulated signal. The splitting of this level is dependent on the extinction ratio (ER) of the IM payload. The reduced label eye opening obtained with a payload extinction ratio of 5 dB proved sufficient for label detection. Figure 5e shows the BER curves for both the post- and precompensation schemes as well as in the back-to-back case. It can be seen that for the FSK label, little difference is measured between the two schemes after a single 50 km SMF span. A 2 dB power penalty compared to back-to-back is obtained at a BER of 10^{-9} in both cases. For the IM payload signal, the precompensation scheme displays significantly improved performance over post-compensation, thus becoming the preferred choice for further transmission experiments.

IM/FSK label swapping is achieved by first erasing the FSK label and then imprinting a new FSK label through wavelength conversion. For label erasure, a MZI-SOA configured

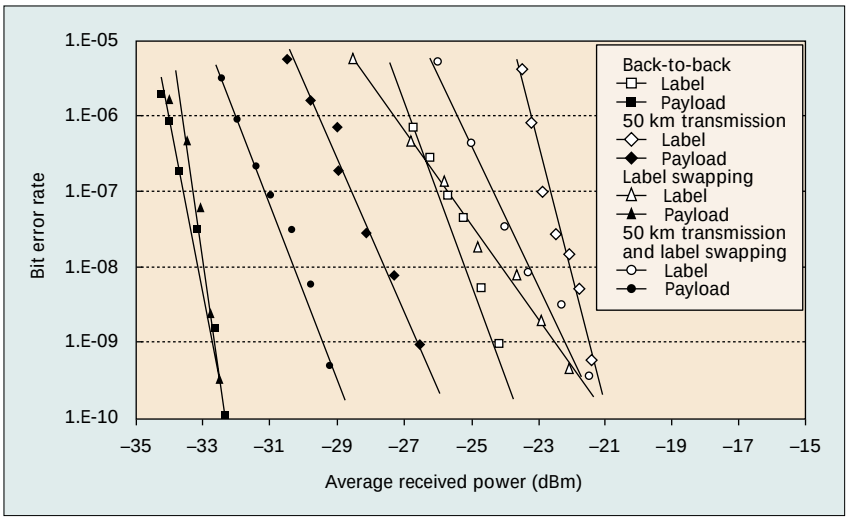

FIGURE 6. BER vs. received power for label swapping, both before and after 50 km transmission over SMF.

to perform wavelength conversion and thus preserving the IM payload information was used, as shown in Fig. 4. For label reinsertion, an additional EAM was used to impress the new FSK label signal through wavelength conversion by cross-absorption modulation. The BER results are shown in Fig. 6, where it can be observed that the performance of the label swapped signal is close to the back-to-back measurements mainly due to the regenerating effect of the MZI-SOA. The bit error rate was also measured after the transmission of the optical labeled signal over 50 km of SMF before the swapping operation. The results, also shown in Fig. 6, revealed a 2–3 dB penalty in the swapped signal compared to the back-to-back case. This is slightly better than the penalty of the signal directly after transmission. Therefore, the feasibility of transmission and label swapping of the orthogonally modulated IM/FSK signal was clearly demonstrated at 10 Gb/s.

CONCLUSIONS

In this article two novel optical labeling techniques that can be used for fast forwarding of IP bursts of packets in labeled optical burst switched networks have been presented. A comparison of both proposed schemes revealed that IM/FSK is preferred as an implementation option, primarily due to its simplicity in the generation and detection of the optical FSK signal, as well as because it imposes less stringent requirement on the laser source linewidth. The transmission performance of an IM/FSK signal was investigated at 10 Gb/s over a 50 km dispersion compensated single-mode fiber span using two dispersion compensation schemes. Furthermore, label swapping was demonstrated using label erasure in an MZI-SOA wavelength converter and label reinsertion in an electro-absorption modulator. It is shown that the 2R regenerative property of the SOA-MZI, used for label erasure can significantly enhance transmission performance of the labeled optical signal. The power penalty of single-hop transmission and all-optical label swapping was found to be less than 2 dB in total, which further strengthen the feasibility of using the orthogonal IM/FSK modulation labeling for future IP-over-WDM networks. Finally, in this article we have also presented a label-controlled switch architecture suitable for the aforementioned labeling techniques that efficiently integrates an arrayed waveguide grating router with a set of two-level label swappers, configured to perform wavelength conversion and thus to preserve the IM payload information and to erase the FSK or DPSK data.

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BIOGRAPHIES

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PALLE JEPPESEN is an electrical engineer (M.Sc. in electrophysics) and graduated from the Technical University of Denmark (DTU) in January 1967. In addition he received a Lic. techn. (Ph.D.) degree in 1970 and a Dr. techn. (D.Sc.) degree in 1978 from DTU. From 1968 to 1969 he was a research associate at Cornell University, Ithaca, New York, and from 1969 to 1970 a project engineer at Cayuga Associates, Ithaca; at both places he did research in the field of GaAs Gunn effect microwave oscillators. From 1970 to 1998 he was an assistant, associate, research, and full professor at the Department of Electromagnetic Systems (EMI), DTU, first in microwave electronics, and since 1974 in optical communications. At EMI he was head of Optogroup from 1974 to 1988 and head of the Center for Broadband Telecommunications from 1988 to 1998. Since 1998 he has been a professor in optical communications at Research Center COM, DTU, where he heads the Systems Competence Area. His current research interests are optical label switching, 40 Gb/s WDM optical communication, including dispersion maps and WDM devices, and 160 Gb/s optical communication, including Raman amplification and optical signal processing.